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The 1717 Eruption of Volcán de Fuego, Guatemala: Cascading Hazards and Societal Response

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Abstract

Assessing and communicating the risks posed by natural hazards requires not only a thorough understanding of the hazards themselves but also an understanding of the spatial and temporal impact of successive events from the same source(s). This approach is enhanced by the lens of time, which is often missing from modern responses to recent hazards. Archaeological studies, in contrast, examine the long-term consequences of hazardous events, but often lack details of the event chronology and immediate human impact that are available for recent events. Here we show ways in which historical records can bridge the gap between modern and prehistoric studies. We focus on the volcanically and seismically active region that hosts the capital city of Guatemala, a city that has been relocated twice in response to hazardous events since its original founding in 1527. More specifically, we examine documents – “*Autos Hechos Sobre el Lastimoso, Estrago y Ruina que Padecio esta Ciudad de Guatemala ...*” [Autos] – that were collected in response to a cascading sequence of volcanic, seismic and mudflow events in 1717 to support a request to the Spanish government to relocate the capital city for a second time. These documents provide exceptional detail about the location of the witnesses, the nature of the hazardous activity and the response of local communities. This detail allows us not only to reconstruct the sequence of events but also to link volcanic activity at Volcán de Fuego to local seismicity and mudflows from Volcán de Agua, which we interpret as triggered by magma intruded after the eruption of Fuego ceased. At the same time, the long and well documented history of the region allows us to examine ways in which a single catastrophic event – in this case a large rainfall-triggered debris flow from Agua in 1541, which destroyed the first capital city – can reverberate through the centuries and affect the response of the local community almost 200 years

later, in 1717. The long-term effects are particularly apparent because both the origin and affected area of the mudflow hazard was very different in the two cases. This example thus illustrates the importance of “memorability” (e.g., Slovic, 2000) in both the perception of, and response to, hazardous events.

1. Introduction

Recent volcanic eruptions, such as that of Eyjafjallajökull volcano in Iceland in 2010, have stimulated important interactions among scientists, social scientists and emergency managers. Such studies of recent events tend naturally to focus on immediate impacts; associated hazard management studies focus on responses to immediate physical impacts of hazard (*vulnerability*), often at the expense of developing long-term (and sustainable) strategies for hazard mitigation (*resilience*; e.g., White et al., 2001). This approach ignores the ‘long shadow’ (e.g., Grattan and Torrence, 2007) of such disasters, where ‘long’ refers to time scales relevant for either political or cultural change (e.g., Birkmann et al., 2010; Diamond and Robinson, 2010). A long view is provided, in contrast, by archaeological studies of the impact of past volcanic disasters on human societies (e.g., Sheets and Grayson, 1979). A challenge to archaeological studies, however, is that causality must be assumed rather than proven (Coombes and Barber 2005; Leroy 2006). The time gap between archaeological and present day research can be bridged by the historical record, which contributes robust chronologies that allow cause and effect to be linked (e.g., Vittori et al., 2007).

Here we draw on documentary sources from eighteenth century Guatemala to examine an unusual cascading sequence of events that affected the second capital of Guatemala, Santiago de Guatemala (now Antigua; Fig. 1), in August and September 1717. The experiences of 1717 prompted debate among Santiago’s inhabitants regarding the situation of the city, which had been relocated to this (higher) site in the aftermath of a disastrous mudflow from the dormant Volcán de Agua that destroyed the original Spanish capital in 1541 (14 years after it was founded). Debate after the 1717 events centered on the precise nature of the hazards and risks posed to the city by nearby volcanoes, specifically Agua and neighboring, frequently active, Volcán de Fuego. The extensive documentation generated as these risks and hazards were assessed reveals a

range of perspectives and understandings; particularly striking, however, is the extent to which the 1541 event loomed large in the memory of the city's population, and served to inform the arguments of those who supported a second relocation of the Guatemalan capital. This is the side of the debate that is reflected in the *Autos*. Detailed analysis of these documents allows us not only to reconstruct the sequence, and analyse the nature, of the events that occurred in 1717, but also to explore the role of past events on the response of the population to an immediate crisis.

2. Background

It is well known that disastrous events can act as natural experiments (Diamond and Robinson, 2010) and/or catalysts of change (e.g., Burby et al., 2000; Perez, 2001; Birkmann et al., 2010). Change may occur by migration (abandoning the hazardous location) or adaptation, such as risk-based land use planning. To be effective, such planning must balance the benefits, as well as the drawbacks, of living in hazardous areas (e.g., White et al. 2001; Glavovic et al., 2010), and engage both community members and government officials (e.g., Cronin et al., 2004; Cashman and Cronin, 2008; Ricci et al., 2013). A key factor that affects community perceptions of risk is the *memorability* (and imaginability) of individual hazards (e.g., Slovic, 2000), such that an event that is memorable within the community for its real *or perceived* impact will be weighted more heavily in planning decisions than an event that is not as easily imagined. A modern example is the 1979 Three Mile Island nuclear accident in the US and the effect of that accident on perceptions of risk related to nuclear power (e.g., Slovic et al., 1982; Kasperson et al., 1988). A different perspective on memorability can be found in studies of oral traditions. When stories must be passed orally from generation to generation, a community disaster may become “a defining experience that passes into shared memory” (Perez, 2001). In this way, inherited stories, whether oral or written, are often preserved where the knowledge contained is critical to community survival (e.g., Barber and Barber, 2006), and thus may influence community planning of future generations.

The long history (~ 300 years) of Spanish colonisation in Guatemala, which was centered on the city of Santiago, produced an extensive written record of hazard events in the area around Volcán de Fuego [Fuego] and neighboring Volcán de Agua [Agua]. Both

volcanoes form part of the central Guatemala arc (Fig. 1). Fuego has been one of the most persistently active of the Guatemalan volcanoes, with 57 confirmed eruptions, and several more unconfirmed, since the arrival of Spanish colonists in 1524 (Smithsonian Institute, Global Volcanism Program [GVP] database). Agua, in contrast, has no documented eruptions in the Holocene (Bonis and Salazar, 1973; Schilling et al., 2001; GVP). It has had, instead, numerous mudflows that have typically affected the area to the north of the volcano, including the first capital city (Peraldo Huertas and Montero Pohly, 1996).

Fuego is basaltic andesite in composition, and most of its eruptions have been moderate in size and intensity (VEI 2 or 3; GVP). At the extremes are periods of persistent low level ‘open vent’ activity (Lyons et al., 2010), and larger (VEI 4) eruptions (Rose et al., 1978; Lyons et al., 2010; GVP). Recorded activity is episodic, with four 20-70 year periods of high activity accounting for 75% of the total number of eruptions (Fig. 2). Interestingly, this episodicity appears to be regional, such that activity at Fuego mirrors the rest of the Central American volcanoes (Martin and Rose, 1981). More importantly, as evidenced by the *Autos*, the frequent activity meant that the inhabitants of Santiago de Guatemala in 1717 were familiar with Fuego’s range of volcanic activity.

Mudflows from Agua also vary in intensity, the most severe being that of September 1541 (Schilling et al., 2001). The mudflow was caused by a debris flow that originated from the volcano’s summit after unusually heavy rainfall. In this respect the event was similar to the devastating debris avalanche and resulting debris flow from dormant Casitas volcano, Nicaragua, in 1998, that was caused by intense rainfall associated with Hurricane Mitch (e.g., Schilling et al., 2001; Scott et al., 2005). The most recent mudflow to affect the area near Agua was also caused by heavy rains associated with Tropical Storm Agatha in 2010; again the flows travelled northward towards what is now the *aldea* (canton) of San Miguel Escobar in Ciudad Vieja, which occupies the same site as the capital that was destroyed in 1541 (Matthew, 2012). Mudflows that affect other sectors of the volcano are rare. One such event occurred in September 1717, when mudflows associated with a large regional earthquake devastated areas on the southwest flank of the volcano. These flows are the focus of our study.

In 1717, Guatemala was part of the Spanish Empire. Ruled by the Spanish monarch, it was governed at a regional level by a complex hierarchy of royal officials, of whom the most senior was the President of the *Audiencia*, who resided in Guatemala and had oversight over a vast area comprising almost the whole of Central America. Municipal affairs at the level of the city were in the hands of the *cabildo*, or council, staffed by prominent members of the local community. The *Autos* analysed in this paper were the product of the efforts of *cabildo* officials in Santiago de Guatemala (Antigua). They were compiled in the aftermath of the events of August-September 1717 in response to the demands of many of its residents to relocate the city. *Cabildo* officials were themselves residents of long-standing, had experienced similar events before, and thus shared the view of many other city dwellers regarding the need for relocation. It was with this purpose in mind that the *cabildo* empowered *alcalde ordinario* Juan de Rubayo Morante to initiate inspections of the local area, interview key witnesses, and dispatch these testimonies and inspection reports to the Crown, whose approval was required before any process of relocation could begin. The resulting file, comprising over 250 manuscript pages, was entitled “*Autos Hechos Sobre el Lastimoso, Estrago y Ruina que Padece esta Ciudad de Guatemala ...*” (henceforth, *Autos*), a copy of which is housed in the Archivo General de Centro América (AGCA) in Guatemala City.

The 1717 evidence-gathering exercise failed to gain the Crown’s support for relocation, and the capital was moved to its current location, Guatemala City, after the earthquake of 1773 (Lutz, 1994; Musset, 1996; Peraldo Huertas and Montero Pohly, 1996). Despite their lack of political success, however, the *Autos* remain an exceptionally valuable source for scholars. They describe a succession of natural disasters in 1717 that began with a VEI 4 eruption (GVP) of Volcán de Fuego on August 27-29 and culminated with a series of severe local earthquakes and major mudflows from Volcán de Agua in late September and early October. Taken together, these testimonies represent a remarkable historical record of scientific and social significance. From a scientific perspective, they provide important insight into a rare example of cascading hazards, where activity at one volcano appears to have triggered events at a neighboring volcano. From a social science perspective, these documents show that the (over-) reaction that

prompted this early example of hazard data collection derived explicitly from memories of the catastrophic (defining) event in 1541.

3. Methods

The *Autos* comprise 45 separate documents, including the testimonies of 20 individuals, among whom were municipal officials and other *vecinos* who had witnessed these (and in many cases prior) events, as well as residents of distant towns consulted for the specific purpose of recording distal effects. The sources are by no means unproblematic. The motives that informed local officials as they gathered testimonies and wrote their reports – that is, production of the *Autos* to support the *cabildo*'s case for the city's relocation – raises the possibility that some of the language was embellished for effect. Yet close analysis of the documents reveals a striking similarity among the accounts with regard to both the timing and nature of the activity; the accounts also show that the events of 1717 were both distinct from, and in combination more severe than, those that had occurred within living memory.

Critical for our analysis of the source material has been collaboration across disciplines, and the pooling of expertise in both volcanology and the history of colonial Spanish America. This multi-faceted approach to translating and interpreting the evidence contained in the testimonies and reports has enabled us to contextualize and extract (1) geologic information, (2) details of event timing and (3) information about event impact. We have also been able to place the witnesses in specific (and various) locations at the time the events occurred, and to record these in a GIS database, which in turn allowed us to assess the spatial as well as temporal reach of the events experienced (Fig. 3). In the text below, we reference individual testimonies by number (T1, T2, etc.), which are keyed to witness locations shown in Figure 3 and included in Table S1 (Supplementary Material). Where individuals occupied multiple locations in the aftermath of the events, they are shown in multiple places on the maps. Throughout this process we have also considered ways in which the community perceived and responded to the events of 1717, in particular how these were shaped by the memory of the disaster that destroyed the original city of Santiago de los Caballeros in 1541.

Language also poses challenges. In part this is due to the different meanings that certain terms carried in the eighteenth century: *vecino*, for instance, meaning neighbour in modern Spanish, referred at the time to a prominent (Spanish) citizen; identifying witnesses as such was likely intended to indicate the reliability of the source and the veracity of the evidence they provided. In part it is also because this was a time when scientific terms to describe the geological effects of events of this kind had not yet to come into common usage. For this reason, eyewitnesses, officials, and inspectors resorted to a range of, often impressionistic, terms to convey the impacts they could see, as well as the experience of what they had heard and felt. Thus, for example, the source and/or morphological changes related to geophysical flows (water, debris, lava) were described with a wide range of terms: *abra* (an opening, potentially also a crack or fissure), *boca* (mouth; a term that is still in use today in Spanish and Italian to refer to a volcanic vent), *respiradero* (vent), *reventazon* (in this context likely meaning something burst or blown up), *zanja* (ditch) and *barranca* (ravine or gully).

Careful reading of the sources, moreover, alerts us to differences in the words chosen by witnesses to describe particular effects and impacts. Especially important in this context are words used to describe the variety of sounds associated with the activity being experienced. The term *ronroneo* (purring sounds), for instance, appears in descriptions of what we interpret, given the context, as short pulses of steam release from Fuego. More ambiguous – even according to the Real Academia Española’s *Diccionario de la lengua española* – are the terms *retumbo* (rumbling, reverberating, or very loud sound), *bramido* (roaring or bellowing sound), *estruendo* (very loud sound), and *traquido* (sound associated with a shot from a firearm). Some clarity may be brought to understanding the meaning of these terms in the *Autos*, when we note that whilst *retumbo* and *bramido* appear in testimonies reporting distal effects (T1, T11, T13), witnesses who were present in Santiago de Guatemala or in the vicinity of either Fuego or Agua at the time the events took place used the term *retumbo* and *temblor* (tremor) to describe activity that was ongoing from the end of August and into October, and *estruendo* and *traquido* only when describing the sounds associated with the beginnings of activity at Fuego (end of August), and/or immediately preceding the mudflow from Agua at the end of September (e.g. T5, T7). We return to these distinctions in the discussion.

4. Results

The *Autos* describe a sequence of natural events that began with a large eruption at Fuego on August 27-29, 1717, and ended with a destructive local earthquake on September 29 and subsequent south-traveling mudflows from Agua. Below we summarize observations of the eruption, the subsequent geophysical activity, and the events of late September.

4.1 Eruption of Fuego, August 27-29, 1717

Eighteen of the documents in the *Autos* describe the eruption of Fuego. All concur that the eruption occurred on August 27th and 28th (e.g., T5), although some witnesses say that it continued into August 29th (T7, T8 and T14). The first signs of activity were small ash pulses early in the evening of August 27th (T14); the main phase started later that evening (T11, T16, T34). For many of the witnesses, the first indications of activity were not visual, but rather audible, with the term *estruendos* being used to convey the idea that the sounds were both frightening and loud; there are also indications that these became increasingly so as the night wore on (T8). By the following day, emitted ash obscured the daylight and witnesses described “rivers of fire” descending from the summit; these “rivers” contained variously sized rocks and traveled with such force that they uprooted trees (T44). We interpret these to be pyroclastic flows produced by deposition either directly from the eruption column or from collapse of advancing lava flows, as seen at Fuego in 1974 (Rose et al., 1978).

Predictably, accounts of the activity vary with witness location (Fig. 4). Witnesses who were relatively close to the volcano (within 20 km; e.g., T1, T34, T44) focused on the plume that reached “high” into the air, starting on August 27th. They described *estruendos*, *retumbos* (rumbles), *temblores* (tremors), and shaking of the ground during the eruptive activity (T1, T5, T34). Confirmation comes from a witness in San Pedro Metapán (El Salvador; located approximately 50 leagues from Santiago de Guatemala), who reported tall *llamas* (flames) of fire on the night of August 28th (T11). *Retumbos* were also heard at great distances from the volcano, as reported by the two witnesses in

San Pedro and San Miguel (El Salvador), who either ‘experienced’ (T13) or ‘heard’ (T11) *retumbos* during the August 27-28 eruptive activity.

Direct damage from the eruption was worst in the valley between Fuego and Agua, including the pueblos of Alotenango and Ciudad Vieja (T26). Although the inhabitants of Santiago de Guatemala were not directly affected by the eruption, many were terrified by the combination of the fire, rocks, smoke and ash:

“... Que es cierto ... que los terremotos y otros graves perjuicios, que se han experimentado en esta ciudad, provienen de los volcanes inmediatos a ella, como se ha experimentado en muchas ocasiones, y especialmente la noche del día veinte y siete de Agosto pasado de este presente año, y el día siguiente en que el uno de ellos abortó voraces lenguas de fuego y humo, cuyo estruendo aterrizó a todos los habitantes de esta ciudad...”

“It is true ... that the earthquakes and other serious afflictions that have been experienced in this city, derive from the volcanoes which lie nearby, as has been experienced on many occasions, and especially on the night of 27 August of this year and the following day when one of these aborted voracious tongues of fire and smoke, the noise of which terrorized all of the inhabitants of this city.” (T5)

4.2 Post-eruptive activity – August 29 – September 29, 1717

During, and for at least 33 days following, the eruption of Fuego on August 27th, the volcano showed signs of unrest in the form of both *retumbos* and *temblores* (T1, T8, T14, T44). According to accounts in the *Autos*, *retumbos* were primarily heard (T5, T10), although in some instances they were also felt (T1, T14); the *temblores* often mentioned in the same context were always felt (ground shaking). Witnesses in proximal locations insisted that both were from sources near (T10), or even “inside” (T5), the volcano.

During the same period, the *Autos* also provide numerous descriptions of *abras* (openings), *bocas* (mouths), *respiraderos* (vents) *zanjas* (ditches), and

barrancas (ravines), the latter said to have increased from meters to tens to hundreds of meters in width and depth (T2, T5, T8, T10; T14, T15, T27, T28). It is unclear from the accounts how many of the *barrancas* formed during, as opposed to after, the August eruption. The testimonies are clear, however, that there were major changes in geomorphology on Fuego during this time period (e.g. T5, T7, T17):

“...con la ocasión del reconocimiento que hizo del dicho Volcán de Fuego, temiendo el que sus piedras no atajasen el dicho rio desagüe de esta ciudad y de dichas haciendas, subió parte de el arriba como hasta más que medio volcán, y vio una barranca que corre a la cima para abajo, tan profunda que le causó terror y miedo, que al parecer tendrá como hasta cien varas de hondura, y de ancho como media cuadra, la cual le dijo un indio que llevaba en su compañía que era nuevamente abierta con la ocasión del fuego que había echado porque antes de él solo era una pequeña barranquilla de vara y media de hondo, por donde con facilidad bajaban y conducían madera...”

“...at the time of the survey of Volcán de Fuego which he conducted ... [due to concerns] that its rocks might block the river drainage of this city and [surrounding] haciendas, he climbed more than half-way up the volcano and saw a ravine that ran from the summit downwards, so deep that [on seeing it] he felt terror and fear. It appears to be up to 100 varas in depth [~83m], and about a half cuadra in width [125m], and according to an Indian who accompanied him, it had opened recently, at the same time as the fire spewed [by the volcano], because previously it was only a shallow ravine, 1.5 varas in depth, down which they comfortably transported wood...”

(T5)

This witness also noted that the *barranca* must have carried a large current of water because of the branches and trees that it had transported to the river. Other witnesses

claimed that another *barranca* had formed from the volcano's summit to the south (T14, T17), and that additional openings produced smoke or steam, and emanated heat and a stench so unpleasant that it made people feel ill (T14, T15).

During the same period, seven of the accounts in *Autos* describe an unusual sensation that they felt when traveling near the volcano, which they likened to walking on hollow ground, or the noise made by horses or carriages in motion (T1, T7, T14, T17, T29, T44). A report from the eastern slopes of Fuego (T15) recounts more specifically the *sensation* that the volcano was either hollow (perhaps reinforced by the appearance of sinkholes (*hoyo* and *apertura*) near Alotenango, T6, T17, T29), or that there was a subterranean *bóveda* (vault) beneath it:

“...y que ...las cabalgaduras ... con su piso parecía pisaban sobre una bóveda y así mismo vieron salir algún humo del centro de dicho barranca como de unos ronroneos expeliendo tanto calor y hedor...”

“...And .. it felt as though their horses were treading over a vault and they also saw some steam rise from the said ravine, like purrs releasing a lot of heat and odor...”

4.3 Earthquake of September 29, 1717

On the evening of September 29, 1717, several large earthquakes inflicted significant damage on Santiago de Guatemala and the surrounding pueblos, with some loss of life (T1). One eyewitness estimated that the earthquakes destroyed half the capital (T31). Although bias could have led to exaggerated impacts, the adverse impacts were real, as indicated by one account that provided a detailed and specific list of the damages to important religious and government buildings (T32). Outside the capital, it was said that the earthquakes were felt on the Costa de Escuintla (then called Costa de Escuintepeque), about 70 km south of Santiago de Guatemala (Fig. 4). The most severe damage, however, was reported in Alotenango and Ciudad Vieja, which lie between, and close to, both volcanoes (T10, T12, T29; Fig. 4). Evidence that no earthquake was felt in El Salvador, and the earthquakes were felt most strongly in the vicinity of the volcanoes

(T10, T11, T13, T18), is consistent with a local origin, and indeed many witnesses (T5, T14, T15) were convinced that the earthquakes were caused by the volcanoes:

“...Y que el asentar que dichos terremotos provienen de los volcanes es porque tiene el declarante su residencia en las haciendas que fueron del Capitán Don Joseph de Castillo, que están casi en la falda del Volcán de Fuego por un lado, y por el otro lado con inmediación al de Agua, y por ello hallándose en el campo le cogieron dichos terremotos, en el, los cuales sintió con imponderable fuerza, o estrépito, y tal que fue preciso arrodillado acercarse de un palo para poderse mantener, y como estaba en la frente del dicho Volcán de Fuego, sintió que el ruido y fuerza de los terremotos salían de él, cuya presunción le confirman los retumbos que hacen mover la tierra porque los oye en el dicho volcán, el que tiene profundas barrancas, o abras recientes...”

“... Because the witness resides in the haciendas ... which on one side extend almost to the slopes of Volcán de Fuego, and on the other lie close to [Volcán] de Agua, he can assert that said earthquakes come from the volcanoes ... he found himself in his fields when the earthquakes struck, with such strength ... that, kneeling, he had to lean on a stick to steady himself. And as he was in front of Volcán de Fuego, he felt that the noise and force of the earthquakes came from it [the volcano]. His assumption is confirmed by the retumbos that make the earth move, because he hears them in said volcano [Fuego] which has [formed] new deep barrancas or openings...”

(T5)

4.4 Mudflow from Volcán de Agua, September 29, 1717

The impact of the September 29 earthquakes was compounded by mudflows from Agua that were apparently triggered by the seismic activity. The flows originated high on the southwest slopes of the volcano and travelled south, away from the primary

population centers, and, it was said, eventually reached the ocean (Fig. 5). Not surprisingly, the pueblos of Masagua and Mistlan on the Rio Guacalate were most impacted by the mudflows (T12). The most detailed description of the source of the mudflows comes from a witness from the pueblo of Escuintla (T23). He was, he said, ‘four leagues’ up the slopes of Volcán de Agua when the flows prevented him from continuing, so he climbed a small hill to get a better view. He describes three separate flows from upslope that first combined, and then split, around the high point where he was standing. The two resulting flows eventually merged into a single flow south downslope from his location (Fig. 6) and continued down the southwest flank of the volcano to join the Rio Guacalate near Escuintla. This account provides the critical observation that the flows originated from new ‘*abras*’ (openings) on the upper slopes of the volcano that hadn’t been there before; for this reason witnesses attributed the flows directly to the September 29th earthquake (e.g., T12).

Several witnesses assert that the resulting mudflow moved with great force, was very large, and carried sizeable sticks and rocks that were deposited along its path (T12, T15, T21). In this respect it sounds like a ‘normal’ debris flow. However, some witnesses also noted that the mudflows had unusual properties: they carried a particularly large volume (sufficient to kill fish in the river) and they were yellow (turning to red as it reached the coast; e.g., T22, T25, T39). These descriptions demonstrate that, in both their source and their character, the mudflows of September 29-30 were different from typical rainfall-triggered mudflows at Agua that (1) originate at the volcano’s summit, (2) travel north toward Ciudad Vieja (e.g., Matthews, 2012), and (3) lack unusual properties such as new ‘openings’ and a yellow color.

Retumbos were also heard during the mudflows (T14). This association led witnesses to relate the September 29 earthquakes, the mudflows, and activity of both volcanoes:

“...y que los retumbos que hacen mover la tierra y se continúan hasta hoy los tiene causados del dicho volcán, por la dicha razón de la inmediación con que está la casa de su habitación, y así por esto como por las abras

que tiene dicho volcán de agua y la que por ellas se dice ha arrojado así a la banda del sur...”

“...And that the retumbos that make the earth move and which continue to this day and he believes to be caused by the said volcano [on the basis that] the house in which he lives is near to it and ... because of the openings that have appeared on Volcán de Agua and down which it has expelled [material] towards the south ...” (T10)

Additional tremors (T11) and mudflows (T22, T23) were reported in October, although the peak of the activity was on September 29-30. Mudflow activity, in contrast, continued to increase over the following days (T22). These events prompted great concerns, particularly that Agua volcano would “entirely burst” and flood the city of Santiago (T18). For this reason, two government officials were instructed to survey both volcanoes, paying particular attention to Agua (reported in T19-T30). Of most concern to the inhabitants of Santiago de Guatemala was the possibility that additional disturbances to either Volcán de Agua or Volcán de Fuego could trigger a collapse from the slopes of one volcano that would block the city’s only drainage, the Rio de Magdalena. They also considered that if Agua experienced another mudflow of the same magnitude but directed to the north, it would “undoubtedly” inundate the city (T6, T7, T8).

5. Discussion

As described above, the *Autos* provide detailed spatial and temporal information about the cascading hazards that commenced with the late August awakening of Volcán de Fuego and ended with damaging local earthquakes, as well as mudflows from Volcán de Agua. They also provide important insight into the (mis)perceptions of some of the population about the nature of those hazards and their potential impact on the capital city. Here we first provide a geologic interpretation of the volcanic activity, the subsequent earthquakes and the culminating mudflows from Volcán de Agua. We then examine the local response to these events, particularly the perception of the people of Santiago de Guatemala that their city was in an unsafe location.

5.1 Interpretation of the events of August-September 1717

The evidence provided above supports previous interpretations of the August 27-29, 1717 eruption as a VEI 4 event (GVP), particularly when compared with detailed descriptions of the most recent VEI 4 eruption in 1974 (Rose et al., 1978). Similarities between the two eruptions include the small precursory episodes of ash release, the high ash plumes that characterized the peak activity, and the accompanying ‘rivers of fire’ (pyroclastic flows). Eruptive activity in 1717 appears, however, to have peaked more quickly (between August 27 and 29), and decayed more rapidly, than the 1974 activity, which continued for two weeks. Another similarity is the formation of hot and steaming *abras* (openings, fissures) on the volcano. In 1717, openings variously described as *abras*, *bocas*, *zanjas*, and *barrancas* appeared on both the south flank and on the east flank (toward Agua). In 1974, fissures and seismicity defined a dominant structural trend along a NNE-SSW axis, while a weakness to the east was suggested by microseismicity immediately following the 1974 activity (Rose et al., 1978).

Several months of microseismicity recorded after the 1974 Volcán de Fuego eruption were interpreted to result from continued activity of the dyke-like conduit responsible for feeding the eruptive activity (Rose et al., 1978). Similar near-surface magma migration may have continued after the end of the visible eruption in 1717. Evidence for continued magmatic activity includes the numerous reported *retumbos* (heard) and *temblores* (felt) earthquakes in September (Fig. 3). Descriptions of *barrancas* and the widely reported sensation of ‘hollow ground’ underfoot in the region between Fuego and Agua may also record surface and near-surface openings created by extension above intruding magma, although this sensation may also record properties of fresh (unconsolidated) volcanic deposits. Heat from young pyroclastic debris, perhaps enhanced by hydrothermal waters, could explain the numerous observations of steam.

The most unusual element of the post-eruption unrest was its culmination in several strong earthquakes on September 29, 1717. Witness testimonies indicate that these events were local, and not regional. Support for this interpretation comes from accounts that show that, although the earthquakes clearly affected parts of the capital city Santiago de Guatemala and were felt to a lesser degree along the Costa de Escuintla (over 70 km to the south), they were felt most intensely in Alotenango and Ciudad Vieja (that

is between Volcán de Agua and Volcán de Fuego; T5; Fig. 4). In fact, some testimonies state explicitly that the earthquake activity was hardly experienced outside of those towns (e.g., T10), and that the towns most severely affected were those on the slopes of Volcán de Agua (T12). This pattern of impact strongly suggests that seismic activity was related to the volcano(es), as so many of the witnesses claimed.

Even more unusual were the mudflows from Agua, which several witnesses claimed to have been triggered by – and coincided precisely with – the seismic activity (e.g. T5). Evidence for triggering includes not only the synchronicity of the events but also emanation of the mudflows from new *abras* on the SW flanks of the volcano (Fig. 6) and abundance of yellow mud, both of which suggest involvement of a hydrothermal system within Agua's edifice. Witnesses also note that the mudflows were accompanied by loud sounds described as *estruendos*. Here the interpretation of the language is important. T10, who was in Ciudad Vieja when the earthquake took place, stated that 'such was the noise that the said volcano [Agua] was making that it terrified him', thinking it to indicate that it had 'burst'. T5's testimony specifically differentiates *retumbos* heard *in* or *from* Fuego at the time of the earthquake, and the *traquido* that came from Agua a short while after, at precisely the moment that he (and, he said, many others) heard a large volume of water 'sprout' from it as well. Thus although it is possible that the *estruendos* may have been generated by sustained crashing of debris carried within the mudflows, we favor the interpretation that this term referred to an explosive source, particularly because the term is sometimes accompanied by strong qualifying adjectives such as 'terrifying' and 'horrifying' (T17). Also important is the absence of reports of heavy rain in 1717 of the kind that was widely reported in relation to the events of 1541 (e.g. in the *Autos*). From this we conclude that the mudflows could not have been generated by excessive rainfall, but instead resulted from groundwater emerging from *within* the volcano.

Taken together, we hypothesize that a magmatic intrusion from Fuego (probably in the form of a dyke) triggered both the September 29 earthquakes and the mudflows from Agua. Support for this hypothesis comes not only from the timing of the events and the nature of the mudflow activity (from apparently new openings and directed down southern, rather than northern, drainages, as well as the large volume of water and

description of yellow mud), but also from reports of increased flow intensity over the next few days (T22), continued flow through October 13 (T22), and a new flow on Oct 15 (T23). Continued emanation of water from these new vents is not consistent with a rainfall-triggered flood, particularly as there is no description of unusual rainfall during this time period. Instead, it strongly suggests rupturing of Agua's hydrothermal system, most likely as a consequence of faulting related to magma movement from Fuego.

5.2 Other examples of cascading volcano hazards involving hydrothermal systems

Magma-induced changes in subsurface hydrologic systems are not uncommon. Manifestations of such changes include phreatic (steam-driven) explosions, changes in hydrothermal systems, groundwater-triggered mudflows and elevated fluxes in local rivers (e.g., Gadow, 1930; Roobol and Smith, 1975; Witze and Kanipe, 2014) or even large landslides (e.g., Voight *et al.*, 1981, 1983; Siebert, 2002). Less common, although not unheard of, is disturbance of a hydrothermal system in one volcano by magmatic activity at a neighboring volcano. Perhaps the most dramatic example of such triggered activity is provided by the 1792 eruption of Unzen volcano, Japan (e.g., Siebert *et al.*, 1987; Siebert, 2002).

Mount Unzen is a volcanic complex that includes the active peak – Fugen-dake – and an older (dormant) peak, the Mayu-yama dome. Fugen-dake erupted on February 10, 1792, after three months of precursory seismicity and phreatic eruptions. Explosive activity gave way to lava flows on March 1; by late April, seismic activity (both felt and heard) had propagated to Mayu-yama, 5 km to the east. An earthquake on April 29 caused the dome to slide 200m, and prompted evacuation of the local population. Three weeks later, on May 21, two strong earthquakes triggered a debris avalanche from Mayu-yama that traveled to the sea; the resulting tsunami killed ~15,000 people, making it the most devastating volcanic disaster in Japanese history (e.g., Siebert *et al.*, 1987). In the weeks following the collapse, hot water continued to flow from the scarp, consistent with release of a pressurized hydrothermal system (Siebert, 2002).

The collapse of Mayu-yama dome was probably caused by saturation of the volcanic edifice as hydrothermal waters migrated in front of advancing magma from Fugen-dake. We suggest a similar scenario for the 1717 mudflows from Agua volcano.

As in Japan, both seismic activity and fissure formation suggest subterranean magma migration between the late August Fuego eruption and the late September earthquakes and mudflows from Agua. Also similar is the sustained emission of initially over-pressured water (sufficient to form new outlets on the flanks of Agua) from a hydrothermal system (evidenced by the temperature, color and smell of the mud). “Remotely”-triggered activity between nearby active and dormant volcanic systems is not often considered in volcanic hazard assessment, either because of its rarity or because triggering has not been recognized. In the specific case of Agua, we suggest that this event was sufficiently unusual (in both location and in the nature of the flows themselves) to add to the anxiety of local communities already stressed by the rather severe eruption and the 33 days of subsequent unrest.

5.3 The long shadow of 1541

The events of August-September 1717, although clearly disruptive, were not catastrophic, at least in comparison with either the events of 1541 or 1773. Since the time of settlement, people in this part of Guatemala had lived with frequent volcanic and seismic activity, and over time some came to recognize that these geophysical events were linked (T36). Why, then, did the events of August to September 1717 provoke such a strong reaction, and lead so many of the inhabitants of Santiago de Guatemala to first evacuate the city and then demand that a new capital be built at a greater distance from Agua? Above we suggest that both the sequence and nature of the events were sufficiently unusual to provoke concern. Here we provide a context for this hypothesis by reviewing the types of information provided by the eyewitnesses and municipal officials regarding previous destructive events related to both eruptions from Fuego and regional seismic activity. We then examine the specific nature of threats posed by Agua, particularly when placed in the context of memories of the catastrophic 1541 debris avalanche and mudflow.

Volcán de Fuego is frequently active, and has been since the Spanish conquest; in fact, Fuego may have been erupting when the Spanish first arrived in the region (Restall and Asselbergs, 2007). The *Autos* demonstrate that local residents were familiar with Fuego’s eruptive history. For example, witnesses explicitly mentioned eruptions earlier in

the century, while municipal officials drew attention to the fact that much of the land was “made by volcanoes” (T17). Official reports about the 1717 events include accounts of the 1705 Fuego eruption, particularly the “exceptional quantity of sand and ash that obscured the sun and the daylight”. More generally, it is stated that more residents of Guatemala had been killed by “fuegos del volcán” than had died from human conflict (T46).

Several of the testimonies in the *Autos* also relate to seismic activity. One witness (T17) stated that the city of Santiago de Guatemala had had to be rebuilt three times since the 16th century because of numerous eruptions and earthquakes, and another (T30) noted that the terrain was ‘sandy’ (probably covered with volcanic ash) and therefore unstable. Accounts documenting damage caused by the earthquake of September 29 include (1) descriptions of the unusual places where Mass was being celebrated because of damage to churches (T2, T30), (2) the total destruction of Alotenango (T29), (3) the estimated costs of rebuilding Santiago de Guatemala (T32, T41), (4) the prominent families who in December 1717 were still living on the streets because of earthquake damage and fear of further tremors (T37, T44), and (5) the effect of these impacts on tax collection (T40, T46). These statements provided the rationale for relocating the city farther away from the “pernicious” and “nearby enemy volcanoes”.

The most striking feature of the *Autos*, however, is the reaction to the mudflows from Agua, which were considered not only unusual but also terrifying. The testimonies show that fears provoked by the mudflows were inflated relative to the actual hazard, and were deeply rooted in memories of the devastating mudflows that destroyed the original capital city in 1541. The 1541 event is specifically invoked by three accounts in the *Autos* (T6, T36, T44), all of which refer to the >600 casualties from that event. This information was transmitted in both oral and written form, an example of the latter being the inclusion in the *Autos* of an extract from Franciscan friar and historian Francisco Vasquez’s 1714 *Cronica de la Provincia del Santisimo Nombre de Jesus de Guatemala*, in which he reviewed the natural disasters that had affected the city since its founding, beginning with the “fatal flood” of 1541. In his description of the event he emphasized the heavy hurricane-generated rainfall that preceded the 1541 mudflows, as well as the terrible noises and ground shaking that accompanied the collapse. Although other witnesses did

not refer specifically to the events of 1541, many did express fears of inundation (by water) during the night of September 29 (T6, T7, T8, T10, T12, T13, T15, T16, T18, T21). More specifically, witnesses were concerned about spontaneous generation of mudflows from the flanks of Agua and consequent blockage of the only drainage from the city (Rio de Magdalena), which ran between the two volcanoes (Fuego and Agua). These fears prompted many to consider moving farther from the volcanoes (T8, T12, T16, T17) and underpinned the arguments made at a public meeting on October 20 to request permission to relocate the capital city (T42).

5.4 Social memory and hazard perception

The critical importance of the 1541 events in the community interpretation of, and response to, the cascading hazards of August-September 1717 provides a clear example of ‘social memory’ (McIntosh et al., 2000) and the role of past events in determining what is perceived to be a disaster (Slovic, 2000; Bankoff, 2004; Perez, 2001). The time frame of community memory and vulnerability has been recognized (e.g., Oliver-Smith 1986; 2002; Bankoff, 2004) but commonly does not find a place within theoretical frameworks of disaster and change (e.g., Birkmann et al., 2010). This omission reflects (1) recent theoretical advances in disaster studies, which focus on either modern disasters or catastrophic collapse of ancient empires, neither of which provide the time resolution required for studies of the impacts of social memories (e.g., Diamond and Robinson 2010; Cooper et al., 2012); (2) the limited number of historical studies of regions prone to repeated events (e.g., Chester et al., 2012); and (3) neglect, until recently, of social memories preserved within oral traditions (e.g., Masse et al., 2007; Cronin and Cashman 2008; Cashman and Cronin, 2008; Cashman and Giordano, 2008 and references therein).

Here we use the 1717 events to illustrate the power of social memory to drive hazard mitigation. For example, population displacement (migration) has been a common response to recent disastrous events (Witham, 2005); it also represents an effective long-term strategy for coping with hazards (Riede, 2014). From this perspective, we can view the inhabitants of Santiago de Guatemala as engaging in a response driven not by irrational fears or misperceptions of the actual hazards, but by attempts to employ a rational strategy to reduce their vulnerability to future events. That they were attempting

to do this within the restrictions imposed by a colonial structure – restrictions that required extensive evidence-based documentation of the natural events and their impacts – provides a unique window into the workings of social memory in a pre-industrial and semi-autonomous community.

The *Autos* also provide an example of an early systematic survey of both a cascade of hazardous events and their impact. The *Autos* are systematic in the formulaic structure of each testimony, which imposes uniformity on eyewitness data collection that presages the format of social science surveys developed more than three centuries later. Of critical importance to our study are data related to the position of each witness, and the extent to which the accounts are based on first hand observations or second hand consultation of eyewitnesses. Also interesting is the application of scientific methods to establish, for example, the local origin of the September 29 earthquake, which they did by soliciting accounts from both local and distant (El Salvador) observers. The *Autos* thus provide “scientific” documentation of hazardous events and their impacts; we suggest that this type of historical documentation is critical to improve both scientific understanding of specific past events and community resilience in the face of future events.

6. Summary and Conclusions

Here we have demonstrated ways in which Spanish archival sources provide key information about both the physical nature of a cascading sequence of natural hazards and a long-term cascade of responses triggered by memories of an early catastrophic event. We have also shown that documentation of the 1717 activity in the form of the *Autos* is unusual from the perspective of natural hazard studies, in that it provides an early example of both a systematic survey of the physical nature and impact of a complex sequence of natural events, as well as a social science survey of human responses to this activity.

The scientific importance of the events of 1717 lies in the suggestion that magmatic (and associated seismic) activity at Fuego triggered a disturbance of the hydrothermal system at neighbouring Agua. Although not unprecedented (e.g., Siebert et al., 1987), remote triggering of hydrothermal activity is unusual, and raises important

questions about hazard assessment of apparently dormant volcanoes such as Agua (e.g., Schilling et al., 2001). Our interpretation of a cascading sequence of hazards transferred from Fuego to Agua also provides a new and integrated perspective of the 1717 activity. This integrated view contrasts with previous geologic and historic interpretations, which consider, separately, the volcanic (e.g., Vallance et al., 2001; Martin and Rose, 1981), seismic (e.g., Feldman, 1993) and hydrologic (e.g., Schilling et al., 2001) events. More broadly, our analysis places the August-September, 1717, activity at Fuego and Agua within a larger framework of volcano-triggered hydrologic hazards that includes the under-appreciated hazard posed by interactions between volcanic systems.

The historical importance of this work lies in the systematic eyewitness accounts assembled in the *Autos*. Organized scientific responses to volcanic eruptions can be dated to the 1883 eruption of Krakatau, which was followed by detailed studies of both regional and global impacts of the event (e.g., Simkin and Fiske, 1983). Modern social science studies of natural hazards, in contrast, start with seminal work in the 1960s that was summarized by Burton et al. (1978). As a social survey, the *Autos* provide surprising detail, particularly given the low physical impact of the events (they did not create a natural disaster). From the ‘long shadow’ perspective, the key observation is that this response – systematic collection of witness accounts from a broad geographic region – can be linked directly to the still-vivid memories of a catastrophic mudflow 176 years earlier. The strength of these memories, as demonstrated by the extremity of the response (a plea by many citizens to relocate the capital city), not only supports Slovic’s (2000) emphasis on memorability as a key element of risk perception, but also shows the potential complexity of responses of past societies to hazardous events. This view supports the idea that natural disasters may be viewed as both historical processes *and sequential events* (Bankoff, 2004).

Finally, our research illustrates the challenges and limitations of working with archival data, as well as the new insights that historical sources provide into the chronology and impact on communities of past natural hazard events. Critical for this type of archival research is collaboration among historians and scientists. The witnesses lacked formal scientific nomenclature for the events described and so the descriptions in the *Autos* are qualitative and of varying detail; the language is descriptive and often

metaphorical, and thus requires (necessarily subjective) translation into modern scientific language, which required the input of volcanologists. Additionally, however, information gleaned from historical sources requires detailed contextual knowledge of the source and the meanings of the words used at the time they were written, as provided by historians. For example, collection of the *Autos* for the express purpose of providing evidence to persuade the Spanish government to support the municipal government's request to relocate the capital city led us to consider the degree of exaggeration in the accounts. We conclude that this context does not seem to have compromised the veracity of the observations of the events themselves and may, if anything, have encouraged the witnesses to include key historical details about past eruptions, earthquakes and mudflows. Explicit consideration of past events (particularly the 1541 mudflow), in turn, helps to explain what appears, initially, to be an extreme over-reaction to a moderate eruption and strong, but not unprecedented, earthquakes and mudflows.

In summary, recent studies have shown the importance of employing the “usable past” (Stump, 2013) to provide immediacy to both hazard forecast scenarios and evidence-based policy recommendations (Reide, 2014). The mudflows from Agua triggered by magmatic activity at Fuego provide such an example, and suggest the importance of assessing volcanic hazard from regional, as well as the more typical single-volcano, perspectives. At the same time, this work illustrates the role of memory in risk perception. Understanding communal memories is crucial not only for effective risk communication and improved resilience, but also for inferring causal relationships between hazardous events and apparent responses in historical and archaeological records.

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Figure Captions

Figure 1 Location map showing the three capital cities of Guatemala and the nearby volcanoes. The cities are currently known as Ciudad Vieja (formerly Santiago de los Caballeros, founded in 1527), Antigua (formerly Santiago de Guatemala, relocated in 1542), and Guatemala City (relocated in 1773 following a large regional earthquake). The volcanoes Atitlan, Fuego, Agua and Pacaya lie along the Central America volcanic arc. All have been active during historical times except Agua.

Figure 2 Eruptive history of Fuego volcano since 1524, when the Spanish first arrived in the area. Data are from the Smithsonian Global Volcanism Program database [<http://www.volcano.si.edu/>] and provide a measure of the eruption size using the Volcano Explosivity Index [<http://volcanoes.usgs.gov/images/pglossary/vei.php>]. VEI 4 eruptions of 1717 and 1974 are highlighted, as is the only other VEI 4 eruption between 1524 and 1717, in 1581.

Figure 3 Map showing the approximate location of witness testimonies. Where the witnesses traveled to survey the effects of the different events, they are placed in all relevant locations. See Table S1 (Supplementary Material) for details.

Figure 4 Map showing the witness locations and inferred intensity (yellow, low intensity to orange, high intensity) of the September 29, 1717 earthquake. Key is the evidence from witnesses in El Salvador that they did not feel this event, which means that it was local. Also important is the evidence that the damage was most severe in Alotenango, which lies between the two volcanoes.

Figure 5 Map showing the witness locations and inferred intensity (pale green, low intensity to blue, high intensity) of the September 29 mudflows from Agua. Importantly these flows emanated from the southwest slopes of Agua and traveled south, and thus did not affect the capital city.

Figure 6 Sketch map from the Autos showing the new boccas formed on the flanks of Agua that fed the September 29 mudflows (from witness T23). The witness shows the flows merging upslope of him, splitting around high ground and converging down slope; the flow eventually fed into the Rio Guacalate near Escuintla. Reproduced courtesy of the Archivo General de Centro América, Guatemala City.

The 1717 Eruption of Volcán de Fuego, Guatemala: Cascading Hazards and Societal Response

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Abstract

Assessing and communicating the risks posed by natural hazards requires not only a thorough understanding of the hazards but also an understanding of the spatial and temporal impact of successive events from the same source(s). This 4 dimensional approach requires the lens of time, which is often missing from modern responses to recent hazards, but also details of the event chronology and immediate human impact, which must be inferred from archaeological studies. Here we provide an example to illustrate the use of historical documents to fill this gap. We focus on the volcanically and seismically active region that hosts the capital city of Guatemala, which has been relocated twice in response to hazardous events since its original founding in 1524. More specifically, we examine documents, entitled “*Autos Hechos Sobre el Lastimoso, Estrago y Ruina que Padecio esta Ciudad de Guatemala ...*” [Autos] that were collected in response to a cascading sequence of volcanic, seismic and mudflow events in 1717 to support a request to the Spanish government to relocate the second capital city. These documents provide exceptional detail about the location of the witnesses, the nature of the hazardous activity and the response of local communities to individual events. This detail allows us not only to reconstruct the sequence of events but also to link volcanic activity at Volcán de Fuego to both local seismicity and mudflows from Volcán de Agua, which we interpret as triggered by intruding magma from Fuego. Additionally, the long and well documented history of the region shows how a single catastrophic event – in this case a large rainfall-triggered debris flow from Agua in 1541, which destroyed the first capital city – can reverberate through the centuries and affect the response of the local community almost 200 years later, in 1717, even though the origin and affected area of the mudflow hazard was very different in the two cases. This example thus illustrates the

importance of “memorability” in both the perception of, and response to, hazardous events (e.g., Slovic, 2000).

1. Introduction

Recent volcanic eruptions, such as that of Eyjafjallajökull volcano in Iceland in 2010, have stimulated important interactions among scientists, social scientists and emergency managers. However, such studies of recent events tend naturally to focus on immediate impacts, with the result that hazard management aims to improve immediate physical impacts of hazard (*vulnerability*), often at the expense of developing long-term (and sustainable) strategies for hazard mitigation (*resilience*; e.g., White et al., 2001). This approach, however, ignores the ‘long shadow’ (e.g., Grattan and Torrence, 2007) of such disasters, where ‘long’ refers to time scales relevant for either political or cultural change (e.g., Birkmann et al., 2010; Diamond and Robinson, 2010). A long view is provided, in contrast, by archaeological studies of the impact of past volcanic disasters on human societies (e.g., Sheets and Grayson, 1979). A challenge to archaeological studies, however, is causality must be assumed rather than proven (Coombes and Barber 2005; Leroy 2006). The time gap between archaeological and present day research is the realm of history, which can contribute robust chronologies that allow cause and effect to be linked (e.g., Vittori et al., 2007).

Here we use the historical record of Spanish colonial Guatemala to improve fundamental understanding of volcano-related hazards in the region, and to examine the role of past events on the response of the local population to an unusual cascading sequence of hazards in August and September of 1717. The written record of the area is extensive, because the events of interest occurred near the second location of the capital city of Guatemala, Santiago de Guatemala (now known as Antigua; Fig. 1), which lies close to the active Volcán de Fuego and dormant Volcán de Agua. Importantly, the first capital city – Santiago de los Caballeros – was destroyed by a disastrous mudflow from nearby Volcán de Agua in 1541, only 17 years after it was founded. The immediate consequence was relocation of the city to higher ground; the much more profound, and longer lasting, consequence was not only extended scientific debate about the mudflow origin (e.g., Maudsley, 1899; Anderson, 1908; Carmak, 1973), but also the extent to

which the destruction of Santiago de los Caballeros still looms large in the minds of local inhabitants. Here we examine the impact of the 1541 mudflow as viewed through the lens of a cascading sequence of hazardous events involving both Volcán de Agua and neighboring Volcán de Fuego in 1717 almost two centuries later, events that prompted local citizens to demand relocation of the capital city for a second time.

2. Background

It is well known that disastrous events can act as natural experiments (Diamond and Robinson, 2010) and/or catalysts of change (e.g., Burby et al., 2000; Perez, 2001; Birkmann et al., 2010). Change may occur by migration (abandoning the hazardous location) or adaptation, such as risk-based land use planning. To be effective, such planning must balance the benefits, as well as the drawbacks, of living in hazardous areas (e.g., White et al. 2001; Glavovic et al., 2010), and engage both community members and government officials (e.g., Cronin et al., 2004; Cashman and Cronin, 2008; Ricci et al., 2013). A key factor that affects community perceptions of risk is the *memorability* (and imaginability) of individual hazards (e.g., Slovic, 2000), such that an event that is memorable within the community for its real *or perceived* impact will be weighted more heavily in planning decisions than an event that is not as easily imagined. A modern example is the 1979 Three Mile Island nuclear accident and the effect of that accident on perceptions of risk related to nuclear power (e.g., Slovic et al., 1982; Kaspersen et al., 1988). A different perspective on memorability can be found in studies of oral traditions. When stories must be passed orally from generation to generation, a community disaster may become “a defining experience that passes into shared memory” (Perez, 2001). In this way, inherited stories, whether oral or written, are often preserved where the knowledge contained is critical to community survival (e.g., Barber and Barber, 2006), and thus may critically influence community planning of future generations.

The long history (~ 300 years) of Spanish occupation of the area around Volcán de Fuego [Fuego] and neighboring Volcán de Agua [Agua] provides an unusual opportunity to evaluate both the behavior of the volcanoes and the communities that have grown up in their shadows. Both volcanoes form part of the central Guatemala arc (Fig. 1). Fuego has been one of the most persistently active of the Guatemalan volcanoes, with

57 confirmed eruptions, and several more unconfirmed, since the arrival of Spanish colonists in 1524 (Smithsonian Institute, Global Volcanism Program [GVP] database). Documentation of Fuego's activity is reasonably good because of its proximity to the original capital city of Santiago de los Caballeros, and to the relocated city of Santiago de Guatemala. Agua, in contrast, has no documented eruptions in the Holocene (Bonis and Salazar, 1973; Schilling et al., 2001; GVP). It has had, instead, numerous mudflows that have affected the area to the north of the volcano, including the area occupied by the first capital city (now Ciudad Vieja).

Fuego is basaltic andesite in composition, and most of its eruptions have been moderate in size and intensity (VEI 2 or 3; GVP). At the extremes are periods of persistent low level 'open vent' activity (Lyons et al., 2010), and larger (VEI 4) eruptions (Rose et al., 1978; Lyons et al., 2010; GVP). Recorded activity is episodic, with four 20-70 year periods of high activity accounting for 75% of the total (Fig. 2). Interestingly, this episodicity appears to be regional, such that activity at Fuego mirrors the rest of the Central American volcanoes (Martin and Rose, 1981). More importantly, by 1717, inhabitants of Santiago de Guatemala were very familiar with Fuego's range of volcanic activity.

Mudflows from Agua also vary in intensity, with the most severe being that of September 1541. The mudflow was caused by a debris flow that originated from the volcano's summit after unusually heavy rainfall. In this the event was similar to the devastating debris avalanche and resulting debris flow from dormant Casitas volcano, Nicaragua, in 1998, that was caused by intense rainfall associated with Hurricane Mitch (e.g., Schilling et al., 2001; Scott et al., 2005). The most recent mudflow to affect the area was caused by heavy rains associated with Tropical Storm Agatha in 2010. Much more unusual are mudflows that affect other sectors of the volcano. One such event occurred in September 1717, when mudflows associated with a large regional earthquake devastated areas on the southwest flank of the volcano. It is this event – both its cause and its impact on the local communities – that are the subject of this paper.

In 1717, Guatemala was part of the Spanish Empire; it was ruled by the Spanish monarch, but governed by a complex hierarchy of royal officials at the regional and local level. The historical sources that we analyze here were produced by municipal officials in

Santiago de Guatemala (Antigua) in the aftermath of the events of August-September of that year, and in response to demands by many of its residents that the city be relocated. Officials within the *cabildo*, or municipal government, themselves residents of long-standing, shared the view that in the light of the extent of the damage suffered by the city as a result of the recent earthquake, it was imperative to obtain the required formal royal approval to initiate the process of relocation. It was with this purpose in mind that the *cabildo* empowered *alcalde ordinario* Juan de Rubayo Morante to carry out investigations in the local area, to interview key witnesses, and to dispatch their testimonies, along with other evidence in support of their case, to Spain. The resulting file, comprising nearly 180 densely-written and bound pages, was entitled “*Autos Hechos Sobre el Lastimoso, Estrago y Ruina que Padecio esta Ciudad de Guatemala ...*” (henceforth, *Autos*), a copy of which is housed in the Archivo General de Centro América (AGCA) in Guatemala City.

Individual testimonies contained in the *Autos* describe a succession of natural disasters, beginning with a VEI 4 eruption (GVP) of Volcán de Fuego on August 27th and 28th of 1717 and culminating with a series of severe local earthquakes and major mudflows from Volcán de Agua in late September. Taken together, these testimonies represent a remarkable historical record of social and scientific significance. From a scientific perspective, they provide important insight into a rare example of triggered (cascading) hazards, where activity at one volcano triggers activity at a neighboring volcano. From a social science perspective, the (over-) reaction that prompted this interesting early example of hazard data collection derived explicitly from memories of the catastrophic (defining) event in 1541.

3. Methods

The *Autos* comprise 45 separate documents that record written and oral accounts provided by testimonies of 20 individuals, including municipal officials, eyewitnesses, and residents with experience of prior similar events. Given the motives that led to their production – namely, to support the *cabildo*’s case for relocation of the capital city – we address the issue of credibility at the outset (Leroy, 2006), specifically the possibility the experience, impact and consequences of the events that took place in 1717 may have

been exaggerated for the purpose of enhancing the case for relocation. The similarity between the accounts that discuss the timing and nature of the activity leads us to conclude, however, that this bias did not affect the accuracy of reporting in this regard. At the same time, we are interested in the witness bias from the perspective of assessing the ways in which the response of the community was affected by the longer history of prior damaging events, and most particularly by the memory of the disaster that destroyed the original city of Santiago de los Caballeros in 1541.

Extracting specific geologic information from the *Autos* required first reading and translating the accounts, and then a second translation from the descriptive original language to modern geologic terminology. The formulaic nature of the process of evidence-gathering – a characteristic of Spanish colonial judicial processes – enables us to place the witnesses in specific locations at the time the events they describe occurred, and to record these in a GIS database, which in turn allows us to assess the spatial as well as temporal reach of the events experienced (Fig. 3). Other testimonies provide information about events witnessed from afar, or told to the witness by someone else. Testimonies by witnesses who traveled extensively to collect data are attached to multiple locations on the maps. Each testimony was then reviewed for (1) geologic information, (2) timing of events and (3) information about event impact. In the text below, we reference individual testimonies using the testimony number (T1, etc.), which is keyed to witness locations shown in Figure 3 and included in Table S1 (Supplementary Material).

4. Results

The *Autos* describe a sequence of natural events that began with a large eruption at Fuego on August 27-29, 1717, and ended with a destructive local earthquake on September 29 and subsequent south-traveling mudflows from Agua. Below we summarize observations from the *Autos* of the eruption, the subsequent geophysical activity, and the events of late September.

4.1 Eruption of Fuego, August 27-28, 1717

Eighteen of the documents in the *Autos* describe the eruption of Fuego. All concur that the eruption occurred on August 27th and 28th (e.g., T5), although some witnesses say

that it continued into August 29th (e.g., T7, T8 and T14). The first signs of activity were small ash pulses on the evening of August 27th (T14); the main phase started on the evening of August 27th (T11, T16, T34). For many of the witnesses, the first indications of activity were not visual, but instead were *estruendos* (crashing sounds) that were particularly loud later that evening (T8). By the following day, emitted ash obscured the daylight and witnesses described “rivers of fire” from the summit that contained variously sized rocks that traveled with so much force that they uprooted trees (T44). We interpret these to be pyroclastic flows produced by collapse of advancing lava flows, as seen in 1974 (Rose et al., 1978).

Predictably, accounts of the activity vary with witness location (Fig. 4). Witnesses who were relatively close to the volcano (T1, T34, T44) focused on the plume that reached “high” into the air, starting on August 27th. They also described *estruendos*, *retumbos* (rumbles), *temblores* (tremors), and shaking of the ground during the eruptive activity (T1, T5, T34). In Santiago de Guatemala, it was claimed that the eruption deposited so much ash that people had to cover their eyes to walk through the streets (T34). Witnesses in the capital city also reported that the ‘fire’ from the volcano could be seen at night from <40 (T17) to >100 leagues (222 – 556 km) away (T44). Confirmation comes from a witness in San Miguel (El Salvador; located approximately 50 leagues from Santiago de Guatemala), who reported tall *llamas* (flames) of fire on the night of August 28th (T11). *Retumbos* were also heard at great distances from the volcano, as reported by the two witnesses in El Salvador, who either ‘experienced’ (T13) or ‘heard’ (T11) *retumbos* during August 27-28 eruptive activity.

Direct damage from the eruption was worst in the valley between Fuego and Agua, including the pueblos of Siquinala, Santa Lucia, and Alotenango (T26). Although the *vecinos* (inhabitants) of Santiago de Guatemala were not directly affected by the eruption, many were terrified by the combination of the fire, rocks, smoke and ash:

“... Que es cierto ... que los terremotos y otros graves perjuicios, que se han experimentado en esta ciudad, provienen de los volcanes inmediatos a ella, como se ha experimentado en muchas ocasiones, y especialmente la noche del día veinte y siete de Agosto pasado de este presente año, y el día

siguiente en que el uno de ellos abortó voraces lenguas de fuego y humo, cuyo estruendo aterrizó a todos los habitantes de esta ciudad...”

“It is true ... that the earthquakes and other serious afflictions that have been experienced in this city, derive from the volcanoes which lie nearby, as has been experienced on many occasions, and especially on the night of 27 August of this year and the following day when one of these aborted voracious tongues of fire and smoke, making crashing sounds that terrorized all of the inhabitants of this city.”

(T5)

4.2 Post-eruptive activity – August 29 – September 29, 1717

During, and for at least 33 days following, the eruption of Fuego on August 27th, the volcano showed signs of unrest, particularly in the form of both *retumbos* and *temblores* (T1, T8, T14, T44). According to accounts in the *Autos*, *retumbos* were primarily heard (T5, T10), although in some instances they were also felt (T1, T14); the *temblores* often mentioned in the same context were always felt (ground shaking). Witnesses in proximal locations insisted that both were from sources near (T10), or even “inside” (T5), the volcano.

During the same period, the *Autos* also provide numerous descriptions of ground fissures, or *barrancas* (ravines), that increased from meters to tens to hundreds of meters in width and depth (T2, T5, T14, T15). It is unclear from the accounts whether these fissures formed during, or shortly after, the August 27-28 eruption. At the same time a *brecha* (breach) opened on Fuego from the summit to the east (toward Alotenango; T5, T7, T17):

“... con la ocasión del reconocimiento que hizo del dicho Volcán de Fuego, temiendo el que sus piedras no atajasen el dicho rio desagüe de esta ciudad y de dichas haciendas, subió parte de el arriba como hasta más que medio volcán, y vio una barranca que corre a la cima para abajo, tan profunda que le causó terror y miedo, que al parecer tendrá como hasta

cien varas de hondura, y de ancho como media cuadra, la cual le dijo un indio que llevaba en su compañía que era nuevamente abierta con la ocasión del fuego que había echado porque antes de él solo era una pequeña barranquilla de vara y media de hondo, por donde con facilidad bajaban y conducían madera...”

“...at the time of the survey of Volcán de Fuego which he conducted, [and] fearing that the rocks might block the river drainage of this city and [surrounding] haciendas, he climbed more than half-way up the volcano and saw a ravine that ran from the summit downwards, so deep that [on seeing it] he felt terror and fear. It appears to be up to 100 varas in depth [~83m], and about a half cuadra in width [125m], and according to an Indian who accompanied him, it had opened recently, at the same time as the fire spewed [by the volcano], because previously it was only a shallow ravine, 1.5 varas in depth, down which they comfortably transported wood...”

(T5)

This witness also noted that the *barranca* must have carried a large current of water because of the branches and trees that it had transported to the river. Other witnesses claimed that another *barranca* had formed from the volcano's summit to the south (T14, T17), and that additional openings produced smoke or steam, and emanated heat and a stench that made people ill (T14, T15).

During the same period, seven of the accounts in *Autos* describe an unusual sensation that they felt when traveling near the volcano, which they likened to walking on hollow ground, or the way the ground sounds when horses or carriages were in motion (T1, T7, T14, T17, T29, T44). A report from the eastern slopes of Fuego (T15) recounts more specifically the sensation that a subterranean *bóveda* (cellar) existed beneath the volcano:

“...y que ...las cabalgaduras ... con su piso parecía pisaban sobre una bóveda y así mismo vieron salir algún humo del centro de dicho barranca como de unos ronroneos expeliendo tanto calor y hedor...”

“...And .. it appeared [to those] on horseback that with each step they were treading over a vault and they also saw some steam rise from the said ravine, like purrs releasing a lot of heat and odor...”

Importantly, this account links the sensation of hollow ground directly to the formation of a *barranca* that was releasing both heat and pungent steam.

4.3 Earthquake of September 29, 1717

On the evening of September 29, 1717, several large earthquakes destroyed much of Santiago de Guatemala and the surrounding pueblos, and took many lives (T1). The earthquakes clearly had a local origin (T10, T11, T13, T18), although they were also felt on the Costa de Escuintla (then called Costa de Esquintlapeque), about 70 km south of Santiago de Guatemala (Fig. 4). Critically, all witnesses (T5, T14, T15) were convinced that the earthquakes were caused by the volcanoes:

“...Y que el asentar que dichos terremotos provienen de los volcanes es porque tiene el declarante su residencia en las haciendas que fueron del Capitán Don Joseph de Castillo, que están casi en la falda del Volcán de Fuego por un lado, y por el otro lado con inmediación al de Agua, y por ello hallándose en el campo le cogieron dichos terremotos, en el, los cuales sintió con imponderable fuerza, o estrépito, y tal que fue preciso arrodillado acercarse de un palo para poderse mantener, y como estaba en la frente del dicho Volcán de Fuego, sintió que el ruido y fuerza de los terremotos salían de él, cuya presunción le confirman los retumbos que hacen mover la tierra porque los oye en el dicho volcán, el que tiene profundas barrancas, o abras recientes...”

“... Because the witness resides in the haciendas ... which on one side extend almost to the slopes of Volcán de Fuego, and on the other lie close to [Volcán] de Agua, he can assert that said earthquakes come from the volcanoes ... he found himself in his fields when the earthquakes struck, with such strength ... that, kneeling, he had to lean on a stick to steady himself. And as he was in front of Volcán de Fuego, he felt that the noise and force of the earthquakes came from it [the volcano]. His assumption is confirmed by the retumbos that make the earth move, because he hears them in said volcano [Fuego] which has [formed] new deep barrancas or openings...”

(T5)

The interpretation of a local source is supported by the severe damage reported in Alotenango and Ciudad Vieja, which lie between, and close to, both volcanoes (T10, T12, T29; Fig. 4). The earthquakes also caused significant damage within Santiago de Guatemala - one eyewitness estimated that the earthquake destroyed half the city (T31) – although here the bias of the witnesses would tend to exaggerate the impacts. That said, one account provides a detailed and specific list of the damages to important religious and government buildings (T32).

4.4 Mudflow from Volcán de Agua, September 29, 1717

The impact of the September 29 earthquakes was compounded by mudflows from Agua that were apparently triggered by the seismic activity. The flows originated high on the southwest slopes of the volcano and travelled south, away from the primary population centers, and, it was said, eventually reached the ocean (Fig. 5). Not surprisingly, the pueblos Masagua and Mistlan on the Rio Guacalate were most impacted by the mudflows (T12). The most detailed description of the source of the mudflows comes from a witness from the pueblo of Esquintlapecque (T23). He was ‘four leagues’ up the slopes of Volcán de Agua when the flows prevented him from continuing, so he climbed a small hill to get a better view. He describes three separate flows from upslope that first combined, and then split, around the high point where he was standing. The two

resulting flows eventually merged into a single flow south and downslope from his location (Fig. 6) and continued down the southwest flank of the volcano to join the Rio Guacalate near Escuintla. This account provides the critical observation that the flows originated from new ‘*abras*’ (openings) on the upper slopes of the volcano that hadn’t been there before; for this reason the witnesses attributed the flows directly to the September 29th earthquake (e.g., T12).

Several witnesses assert that the mudflow moved with great force and was very large, and that it carried sizeable sticks and rocks that were deposited along its path (T12, T15, T21). In this it sounds like a ‘normal’ debris flow. However, some witnesses also noted that the mudflows had unusual properties: they were yellow, they had a distinctive and repugnant sulphurous smell, and they were hot enough to kill all of the fish in the river (T14, T15, T17, T18, T19, T21, T22, T25, T36, T39, T44). These descriptions demonstrate that, in both their source and their character, the mudflows of September 29-30 were different from typical rainfall-triggered mudflows at Agua, which originate at the volcano’s summit and travel north toward Ciudad Vieja.

Retumbos were also heard during the mudflows (T14). This association led witnesses to relate the September 29 earthquakes, the mudflows, and activity of both volcanoes:

“...y que los retumbos que hacen mover la tierra y se continúan hasta hoy los tiene causados del dicho volcán, por la dicha razón de la inmediación con que está la casa de su habitación, y así por esto como por las abras que tiene dicho volcán de agua y la que por ellas se dice ha arrojado así a la banda del sur...”

“...And that the retumbos that make the earth move and which continue to this day are caused by the said volcano [which he knows] because the house in which he lives is near to it and ... because of the openings that have appeared on Volcán de Agua and down which it has expelled [material] towards the south ...” (T10)

Additional tremors (T11) and mudflows (T22, T23) were reported in October, although clearly the peak of the activity was on September 29-30. These events prompted great concerns, particularly that Agua volcano would “entirely burst” and flood the city (T18); for this reason, two government officials were instructed to survey both volcanoes, while paying particular attention to Agua (reported in T19-T30). Of most concern to the citizens of Santiago de Guatemala was the possibility that additional disturbances to either Volcán de Agua or Volcán de Fuego could trigger a collapse from the slopes of one volcano that that would block the city’s only drainage, Rio de Magdalena. They also considered that if Agua experienced another mudflow of the same magnitude but directed to the north, it would “undoubtedly” inundate the city (T6, T7, T8).

5. Discussion

As described above, the *Autos* provide detailed spatial and temporal information about the cascading hazards that commenced with the late August awakening of Volcán de Fuego and ended with the damaging local earthquake and mudflows from Volcán de Agua. They also provide important insight into the (mis)perceptions of some of the population about the nature of those hazards and their potential impact on the capital city. Here we first provide a geologic interpretation of the volcanic activity, the subsequent earthquakes and the culminating mudflows from Volcán de Agua. We then examine the local response to these events, particularly the perception of the people of Santiago de Guatemala that their city was in an unsafe location.

5.1 Interpretation of the events of August-September 1717

The evidence provided above supports previous interpretations of the August 27-29, 1717 eruption as a VEI 4 event (GVP), particularly when compared with detailed descriptions of the most recent VEI 4 eruption in 1974 (Rose et al., 1978). Similarities between the two eruptions include the small precursory episodes of ash release, the high ash plumes that characterized the peak activity, and the accompanying ‘rivers of fire’ (pyroclastic flows). Eruptive activity in 1717 appears, however, to have peaked more quickly (between August 27 and 29), and decayed more rapidly, than the 1974 activity, which continued for two weeks. Another similarity is the formation of numerous hot and

steaming *abras* (openings, fissures) on the volcano's flanks. In 1717, fissures appeared on both the south flank and on the east flank (toward Agua). In 1974, a dominant structural trend was identified along a NNE-SSW axis, while a weakness to the east was suggested by microseismicity trends after the 1974 activity (Rose et al., 1978).

Importantly, near-surface magma migration continued after the end of the visible eruption. Evidence for continued magmatic activity includes both the numerous reported *retumbos* (heard) and *temblores* (felt) earthquakes in September, as well as descriptions of barrancas and 'hollow ground' in the region between Fuego and Agua (Fig. 3). Together, these data suggest that subsurface magma intrusion may have created both surface and near-surface openings, perhaps caused by extension above a propagating dyke. Similarly, the several months of microseismicity recorded after the 1974 Volcán de Fuego eruption were interpreted to result from continued activity of the dike-like conduit responsible for feeding the eruptive activity.

The post-eruption unrest culminated in a strong earthquake on September 29, 1717. Testimonies in the *Autos* unambiguously demonstrate that this was a local, not a regional, earthquake. Moreover, although the earthquake clearly affected parts of the capital city Santiago de Guatemala and was felt to a lesser degree along the Costa de Escuintla (over 70 km to the south), the earthquake was felt most intensely in Alotenango and Ciudad Vieja (that is between Volcán de Agua and Volcán de Fuego; T5; Fig. 4). In fact, some testimonies state explicitly that the earthquake was hardly experienced outside of those towns (e.g., T10), and that the towns most severely affected were those on the slopes of Volcán de Agua (T12). This pattern of impact strongly suggests that the earthquake was caused by faulting related to magma intrusion along a fissure or dyke system propagating east from Volcán de Fuego toward Volcán de Agua, consistent with evidence for eastward propagating dykes during the month of September.

Further evidence for lateral magma propagation lies in the mudflows, which several witnesses thought were triggered by the seismic activity. Evidence for triggering includes emanation of the mudflows from new *abras* on the SW flanks of the volcano (Fig. 6), and descriptions of steaming *avenidas* of water and yellow mud that smelled of sulphur, both of which suggest involvement of a hydrothermal system within Agua's edifice. The mudflows were also accompanied by *estruendos* (crashing, or exploding

sounds), which suggests that small phreatic explosions may have occurred in conjunction with vent formation. These observations, together with the absence of reports of heavy rain, show that the mudflows were not generated by excessive rainfall, but instead by groundwater emerging from within the volcano. Taken together, we conclude that there is overwhelming evidence that a magmatic intrusion from Fuego (probably in the form of a dyke) triggered both the September 29 earthquake and the mudflows from Agua.

5.2 Other examples of cascading volcano hazards involving hydrothermal systems

Magma-induced changes in subsurface hydrologic systems are not uncommon. Manifestations of such changes include phreatic (steam-driven) explosions, changes in hydrothermal systems, groundwater-triggered mudflows and elevated fluxes in local rivers (e.g., Gadow, 1930; Roobol and Smith, 1975; Witze and Kanipe, 2014) or even large landslides (e.g., Voight *et al.*, 1981, 1983; Siebert, 2002). Less common, although not unheard of, is disturbance of a hydrothermal system in one volcano by magmatic activity at a neighboring volcano. Perhaps the most dramatic example of such triggered activity is provided by the 1792 eruption of Unzen volcano, Japan (e.g., Siebert *et al.*, 1987; Siebert, 2002).

Mount Unzen is a volcanic complex that includes the active peak – Fugen-dake – and an older (dormant) peak, the Mayu-yama dome. Fugen-dake erupted on February 10, 1792, after three months of precursory seismicity and phreatic eruptions. Explosive activity gave way to lava flows on March 1; by late April, seismic activity (both felt and heard) propagated to Mayu-yama, 5 km to the east. An earthquake on April 29 caused the dome to slide 200m, and prompted evacuation of the local population. Three weeks later, on May 21, two strong earthquakes triggered a debris avalanche from Mayu-yama that traveled to the sea; the resulting tsunami killed ~15,000 people, making it the most devastating volcanic disaster in Japanese history (e.g., Siebert *et al.*, 1987). In the weeks following the collapse, hot water continued to flow from the scarp, consistent with release of a pressurized hydrothermal system (Siebert, 2002).

The collapse of Mayu-yama dome was probably caused by saturation of the volcanic edifice as hydrothermal waters migrated in front of advancing magma. We suggest a similar scenario for the 1717 mudflows from Agua volcano. As in Japan, both

seismic activity and fissure formation provide evidence of subterranean magma migration between the late August Fuego eruption and the late September earthquakes and mudflows from Agua. Also similar is the emission of over-pressured water (sufficient to form new outlets on the flanks of Agua) from a hydrothermal system (evidenced by the temperature, color and smell of the mud). Importantly, this event was sufficiently unusual that it must have added to the anxiety of the local communities, who were already stressed by the rather severe eruption and the 33 days of subsequent unrest.

5.3 The long shadow of 1541

The events of August-September 1717, although clearly disruptive, were not catastrophic, or even disastrous. Citizens of the area had been living with frequent volcanic and seismic activity since the time of settlement, and some recognized the links between these geophysical events (T36). Why, then, did these events prompt a call from many of the inhabitants of Santiago de Guatemala to relocate the capital city farther away from Volcán de Agua? We address this question by first reviewing the types of information provided by the eyewitnesses and municipal officials regarding previous destructive events related to both eruptions from Fuego and regional seismic activity. We then focus on the specific nature of threats posed by Agua, particularly when placed in the context of the catastrophic 1541 debris avalanche and mudflow.

Volcán de Fuego is frequently active, and has been since the Spanish conquest; in fact, Fuego may have been erupting when the Spanish first arrived in the region (Restall and Asselbergs, 2007). The *Autos* demonstrate that the residents of the area were very familiar with Fuego's eruptive history. For example, witnesses T7 and T8 explicitly mention eruptions earlier in the century, and municipal officials recognize that much of the land was "made by volcanoes" (T17). More importantly, official reports about the 1717 events also include copies of reports made after the 1705 Fuego eruption, with descriptions of the "exceptional quantity of sand and ash that obscured the sun and the daylight", and the statement that more residents of Guatemala have been killed by "fuegos del volcán" than died from human conflict (T46).

Several of the testimonies in the *Autos* also relate to seismic activity. One witness (T17) states that the city of Santiago de Guatemala had to be rebuilt three times since the

16th century because of numerous eruptions and earthquakes, and another (T30) notes that the terrain is ‘sandy’ (covered with volcanic ash) and therefore unstable. Accounts documenting damage caused by the earthquake of September 29 include descriptions of the unusual places where Mass was being celebrated because of damage to churches (T2, T30), the total destruction of Alotenango (T29), the estimated costs of rebuilding Santiago de Guatemala (T32, T41), the decline in taxes collected (T40, T46) and the prominent families who, in December 1717, were still living on the streets because of earthquake damage and fear of further tremors (T37, T44). These statements provide the sound economic argument for relocating the city farther away from the “pernicious” and “nearby enemy volcanoes”.

It is clear from the *Autos*, however, that the mudflows from Agua were considered not only unusual but terrifying. Moreover, the testimonies show that the fears provoked by the mudflows were inflated relative to the actual hazard, and were deeply rooted in memories of the devastating mudflows that destroyed the original capital city in 1541. The 1541 event is specifically invoked by three accounts in the *Autos* (T6, T36, T44), all of which refer to the >600 casualties from that event. Importantly, it is clear that this information was transmitted in both written and form, the latter of which is documented by T36, which are extracts from a book written in 1714 by Fray Francisco Vasquez, a Franciscan friar and historian. In the book he reviews natural disasters that had affected the city since its founding, beginning with the “fatal flood” of 1541. In his description of the event he emphasized the heavy hurricane-generated rainfall that preceded the 1541 mudflows, as well as the terrible noises and ground shaking that accompanied the collapse. Several other witnesses (T6, T7, T8, T10, T12, T13, T15, T16, T18, T21) do not refer specifically to the events of 1541, but did express fears of inundation during the night of September 29. More specifically, witnesses worried about spontaneous generation of mudflows from the flanks of Agua, and consequent blockage of the only drainage from the city (Rio de Magdalena), which ran between the two volcanoes (Fuego and Agua). These fears prompted many to consider moving farther from the volcanoes (T8, T12, T16, T17) and underpinned the consensus of a public meeting on October 20 to request permission to relocate the capital city (T42).

5.4 *Social memory and hazard perception*

The critical importance of the 1541 events in the community interpretation of, and response to, the cascading hazards of August-September 1717 provides a clear example of ‘social memory’ (McIntosh et al., 2000) and the role of past events in determining what is perceived to be a disaster (Slovic, 2000; Bankoff, 2004; Perez, 2001). The time frame of community memory and vulnerability has been recognized (e.g., Oliver-Smith 1986; 2002; Bankoff, 2004) but commonly does not find a place within theoretical frameworks of disaster and change (e.g., Birkmann et al., 2010). This omission reflects (1) recent theoretical advances in disaster studies, which focus on either modern disasters or catastrophic collapse of ancient empires, neither of which provide the time resolution required for studies of the impacts of social memories (e.g., Diamond and Robinson 2010; Cooper et al., 2012); (2) the limited number of historical studies of regions prone to repeated events (e.g., Chester et al., 2012); and (3) neglect, until recently, of social memories preserved within oral traditions (e.g., Masse et al., 2007; Cronin and Cashman 2008; Cashman and Cronin, 2008; Cashman and Giordano, 2008 and references therein).

The 1717 example also shows the power of social memory to drive hazard mitigation. Population displacement (migration) has been a common response to recent disastrous events (Witham, 2005); it also represents an effective long-term strategy for coping with hazards (Riede, 2014). From this perspective, we can view the inhabitants of Santiago de Guatemala as engaging in a response driven not by irrational fears or misperceptions of the actual hazards, but by attempts to employ a rational strategy to reduce their vulnerability to future events. That they are attempting to do this within the restrictions imposed by a colonial structure – restrictions that required extensive evidence-based documentation of the natural events and their impacts – provides a unique window into the workings of social memory in a pre-industrial and semi-autonomous community.

The *Autos* also provide an example of an early systematic survey of both a cascade of hazardous events and their impact. The *Autos* are systematic in the formulaic structure of each testimony, which imposes uniformity on eyewitness data collection that presages the format of social science surveys developed more than three centuries later. Of critical importance to our study are data related to the position of each witness, and

the extent to which the accounts are based on first hand observations or second hand consultation of eyewitnesses. Also interesting is the application of scientific methods to establish, for example, the local origin of the September 29 earthquake, which they did by soliciting accounts from both local and distant (El Salvador) observers. The *Autos* thus provide systematic documentation of hazardous events and their impacts for the purpose of improving both scientific understanding and resilience in the face of future events.

6. Summary and Conclusions

Here we have demonstrated ways in which Spanish archival sources provide key information about both the physical nature of a cascading sequence of natural hazards and a long-term cascade of responses triggered by memories of an early catastrophic event. We have also shown that documentation of the 1717 activity in the form of the *Autos* is unusual from the perspective of natural hazard studies, in that it provides an early example of both a systematic survey of the physical nature and impact of a complex sequence of natural events, as well as a social science survey of human responses to this activity.

The scientific importance of the events of 1717 lies in the clear evidence that magmatic (and associated seismic) activity at Fuego triggered a disturbance of the hydrothermal system at neighbouring Agua. Although not unprecedented (e.g., Siebert et al., 1987), remote triggering of hydrothermal activity is unusual, and raises important questions about hazard assessment of apparently dormant volcanoes such as Agua (e.g., Schilling et al., 2001). Our interpretation of a cascading sequence of hazards transferred from Fuego to Agua also provides a new and integrated perspective of these events. This integrated view contrasts with previous geologic and historic interpretations of the 1717 activity, which consider, separately, the volcanic (e.g., Vallance et al., 2001; Martin and Rose, 1981), seismic (e.g., Feldman, 1993) and hydrologic (e.g., Schilling et al., 2001) events. More broadly, our analysis places the August-September, 1717, activity at Fuego and Agua within a larger framework of volcano-triggered hydrologic hazards that include the under-appreciated hazard posed by interactions between volcanic systems.

The historical importance of this work, from a scientific perspective, lies in the systematic eyewitness accounts assembled in the *Autos*. Organized scientific responses to

volcanic eruptions can be dated to the 1883 eruption of Krakatau, which was followed by detailed studies of both regional and global impacts of the event (e.g., Simkin and Fiske, 1983). Modern social science studies of natural hazards, in contrast, start with seminal work in the 1960s that was summarized by Burton et al. (1978). From this perspective, the *Autos* represent a surprisingly detailed response to a series of cascading natural hazards, particularly given the low physical impact of the events (they did not create a natural disaster). From the ‘long shadow’ perspective, the key observation is that this response – systematic collection of witness accounts from a broad geographic region – can be linked directly to the still-vivid memories of a catastrophic mudflow 176 years earlier. The strength of these memories, as demonstrated by the extremity of the response (a plea by many citizens to relocate the capital city), not only supports Slovic’s (2000) emphasis on memorability as a key element of risk perception, but also shows the potential complexity of responses of past societies to hazardous events. This view supports the idea that natural disasters may be viewed as both historical processes and sequential events (Bankoff, 2004).

Finally, this research also illustrates the limitations of working with archival data. Although the witness accounts provide valuable (and often thoughtful) geologic observations, the descriptions are qualitative and of varying detail. In part this derives from their historical context, and the lack of formal scientific nomenclature for the events described. The language is descriptive and often metaphorical, and thus requires (necessarily subjective) translation into modern scientific language. Additionally, information gleaned from historical sources requires detailed contextual knowledge of the source. In the case of the *Autos*, the critical context is that these witness accounts were collected for the express intent of providing documentation for the Spanish government to support the municipal government’s request to relocate the capital city, which raises the concern that the accounts may be exaggerated. Surprisingly, however, this does not seem to have compromised the veracity of the observations of the events themselves. Moreover, this context likely encouraged the witnesses to include key historical details (about past eruptions, earthquakes and mudflows) that help to explain what appears, initially, to be an extreme over-reaction to a moderate eruption and strong, but not unprecedented, earthquakes and mudflows.

In summary, recent studies have shown the importance of employing the “usable past” (Stump, 2013) to provide immediacy to both hazard forecast scenarios and evidence-based policy recommendations (Reide, 2014). The mudflows from Agua that were triggered by magmatic activity at Fuego provide such an example, and suggest the importance of assessing volcanic hazard from regional, as well as the more typical single-volcano, perspectives. At the same time, this work illustrates the role of memory in risk perception. Understanding communal memories is crucial not only for effective risk communication and improved resilience, but also for inferring causal relationships between hazardous events and apparent responses in historical and archaeological records.

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Figure Captions

Figure 1 Location map showing the three capital cities of Guatemala and the nearby volcanoes. The cities are currently known as Ciudad Vieja (formerly Santiago de los Caballeros, founded in 1527), Antigua (formerly Santiago de Guatemala, relocated in 1542), and Guatemala City (relocated in 1773 following a large regional earthquake). The volcanoes Atitlan, Fuego, Agua and Pacaya lie along the Central America volcanic arc. All have been active during historical times except Agua.

Figure 2 Eruptive history of Fuego volcano since 1524, when the Spanish first arrived in the area. Data are from the Smithsonian Global Volcanism Program database [<http://www.volcano.si.edu/>] and provide a measure of the eruption size using the Volcano Explosivity Index [<http://volcanoes.usgs.gov/images/pglossary/vei.php>]. VEI 4 eruptions of 1717 and 1974 are highlighted, as is the only other VEI 4 eruption between 1524 and 1717, in 1581.

Figure 3 Map showing the approximate location of witness testimonies. Where the witnesses traveled to survey the effects of the different events, they are placed in all relevant locations. See Table S1 (Supplementary Material) for details.

Figure 4 Map showing the witness locations and inferred intensity (yellow, low intensity to orange, high intensity) of the September 29, 1717 earthquake. Key is the evidence from witnesses in El Salvador that they did not feel this event, which means that it was local. Also important is the evidence that the damage was most severe in Alotenango, which lies between the two volcanoes.

Figure 5 Map showing the witness locations and inferred intensity (pale green, low intensity to blue, high intensity) of the September 29 mudflows from Agua. Importantly these flows emanated from the southwest slopes of Agua and traveled south, and thus did not affect the capital city.

Figure 6 Sketch map from the Autos showing the new boccas formed on the flanks of Agua that fed the September 29 mudflows (from witness T23). The witness shows the flows merging upslope of him, splitting around high ground and converging down slope; the flow eventually fed into the Rio Guacalate near Escuintla.

The 1717 Eruption of Volcán de Fuego, Guatemala: Cascading Hazards and Societal Response

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Abstract

Assessing and communicating the risks posed by natural hazards requires not only a thorough understanding of the hazards but also an understanding of the spatial and temporal impact of successive events from the same source(s). This 4 dimensional approach requires the lens of time, which is often missing from modern responses to recent hazards, but also details of the event chronology and immediate human impact, which must be inferred from archaeological studies. Here we provide an example to illustrate the use of historical documents to fill this gap. We focus on the volcanically and seismically active region that hosts the capital city of Guatemala, which has been relocated twice in response to hazardous events since its original founding in 1524. More specifically, we examine documents, entitled “*Autos Hechos Sobre el Lastimoso, Estrago y Ruina que Padecio esta Ciudad de Guatemala ...*” [Autos] that were collected in response to a cascading sequence of volcanic, seismic and mudflow events in 1717 to support a request to the Spanish government to relocate the second capital city. These documents provide exceptional detail about the location of the witnesses, the nature of the hazardous activity and the response of local communities to individual events. This detail allows us not only to reconstruct the sequence of events but also to link volcanic activity at Volcán de Fuego to both local seismicity and mudflows from Volcán de Agua, which we interpret as triggered by intruding magma from Fuego. Additionally, the long and well documented history of the region shows how a single catastrophic event – in this case a large rainfall-triggered debris flow from Agua in 1541, which destroyed the first capital city – can reverberate through the centuries and affect the response of the local community almost 200 years later, in 1717, even though the origin and affected area of the mudflow hazard was very different in the two cases. This example thus illustrates the

importance of “memorability” in both the perception of, and response to, hazardous events (e.g., Slovic, 2000).

1. Introduction

Recent volcanic eruptions, such as that of Eyjafjallajökull volcano in Iceland in 2010, have stimulated important interactions among scientists, social scientists and emergency managers. However, such studies of recent events tend naturally to focus on immediate impacts, with the result that hazard management aims to improve immediate physical impacts of hazard (*vulnerability*), often at the expense of developing long-term (and sustainable) strategies for hazard mitigation (*resilience*; e.g., White et al., 2001). This approach, however, ignores the ‘long shadow’ (e.g., Grattan and Torrence, 2007) of such disasters, where ‘long’ refers to time scales relevant for either political or cultural change (e.g., Birkmann et al., 2010; Diamond and Robinson, 2010). A long view is provided, in contrast, by archaeological studies of the impact of past volcanic disasters on human societies (e.g., Sheets and Grayson, 1979). A challenge to archaeological studies, however, is causality must be assumed rather than proven (Coombes and Barber 2005; Leroy 2006). The time gap between archaeological and present day research is the realm of history, which can contribute robust chronologies that allow cause and effect to be linked (e.g., Vittori et al., 2007).

Here we use the historical record of Spanish colonial Guatemala to improve fundamental understanding of volcano-related hazards in the region, and to examine the role of past events on the response of the local population to an unusual cascading sequence of hazards in August and September of 1717. The written record of the area is extensive, because the events of interest occurred near the second location of the capital city of Guatemala, Santiago de Guatemala (now known as Antigua; Fig. 1), which lies close to the active Volcán de Fuego and dormant Volcán de Agua. Importantly, the first capital city – Santiago de los Caballeros – was destroyed by a disastrous mudflow from nearby Volcán de Agua in 1541, only 17 years after it was founded. The immediate consequence was relocation of the city to higher ground; the much more profound, and longer lasting, consequence was not only extended scientific debate about the mudflow origin (e.g., Maudsley, 1899; Anderson, 1908; Carmak, 1973), but also the extent to

which the destruction of Santiago de los Caballeros still looms large in the minds of local inhabitants. Here we examine the impact of the 1541 mudflow as viewed through the lens of a cascading sequence of hazardous events involving both Volcán de Agua and neighboring Volcán de Fuego in 1717 almost two centuries later, events that prompted local citizens to demand relocation of the capital city for a second time.

2. Background

It is well known that disastrous events can act as natural experiments (Diamond and Robinson, 2010) and/or catalysts of change (e.g., Burby et al., 2000; Perez, 2001; Birkmann et al., 2010). Change may occur by migration (abandoning the hazardous location) or adaptation, such as risk-based land use planning. To be effective, such planning must balance the benefits, as well as the drawbacks, of living in hazardous areas (e.g., White et al. 2001; Glavovic et al., 2010), and engage both community members and government officials (e.g., Cronin et al., 2004; Cashman and Cronin, 2008; Ricci et al., 2013). A key factor that affects community perceptions of risk is the *memorability* (and imaginability) of individual hazards (e.g., Slovic, 2000), such that an event that is memorable within the community for its real *or perceived* impact will be weighted more heavily in planning decisions than an event that is not as easily imagined. A modern example is the 1979 Three Mile Island nuclear accident and the effect of that accident on perceptions of risk related to nuclear power (e.g., Slovic et al., 1982; Kasperson et al., 1988). A different perspective on memorability can be found in studies of oral traditions. When stories must be passed orally from generation to generation, a community disaster may become “a defining experience that passes into shared memory” (Perez, 2001). In this way, inherited stories, whether oral or written, are often preserved where the knowledge contained is critical to community survival (e.g., Barber and Barber, 2006), and thus may critically influence community planning of future generations.

The long history (~ 300 years) of Spanish occupation of the area around Volcán de Fuego [Fuego] and neighboring Volcán de Agua [Agua] provides an unusual opportunity to evaluate both the behavior of the volcanoes and the communities that have grown up in their shadows. Both volcanoes form part of the central Guatemala arc (Fig. 1). Fuego has been one of the most persistently active of the Guatemalan volcanoes, with

57 confirmed eruptions, and several more unconfirmed, since the arrival of Spanish colonists in 1524 (Smithsonian Institute, Global Volcanism Program [GVP] database). Documentation of Fuego's activity is reasonably good because of its proximity to the original capital city of Santiago de los Caballeros, and to the relocated city of Santiago de Guatemala. Agua, in contrast, has no documented eruptions in the Holocene (Bonis and Salazar, 1973; Schilling et al., 2001; GVP). It has had, instead, numerous mudflows that have affected the area to the north of the volcano, including the area occupied by the first capital city (now Ciudad Vieja).

Fuego is basaltic andesite in composition, and most of its eruptions have been moderate in size and intensity (VEI 2 or 3; GVP). At the extremes are periods of persistent low level 'open vent' activity (Lyons et al., 2010), and larger (VEI 4) eruptions (Rose et al., 1978; Lyons et al., 2010; GVP). Recorded activity is episodic, with four 20-70 year periods of high activity accounting for 75% of the total (Fig. 2). Interestingly, this episodicity appears to be regional, such that activity at Fuego mirrors the rest of the Central American volcanoes (Martin and Rose, 1981). More importantly, by 1717, inhabitants of Santiago de Guatemala were very familiar with Fuego's range of volcanic activity.

Mudflows from Agua also vary in intensity, with the most severe being that of September 1541. The mudflow was caused by a debris flow that originated from the volcano's summit after unusually heavy rainfall. In this the event was similar to the devastating debris avalanche and resulting debris flow from dormant Casitas volcano, Nicaragua, in 1998, that was caused by intense rainfall associated with Hurricane Mitch (e.g., Schilling et al., 2001; Scott et al., 2005). The most recent mudflow to affect the area was caused by heavy rains associated with Tropical Storm Agatha in 2010. Much more unusual are mudflows that affect other sectors of the volcano. One such event occurred in September 1717, when mudflows associated with a large regional earthquake devastated areas on the southwest flank of the volcano. It is this event – both its cause and its impact on the local communities – that are the subject of this paper.

In 1717, Guatemala was part of the Spanish Empire; it was ruled by the Spanish monarch, but governed by a complex hierarchy of royal officials at the regional and local level. The historical sources that we analyze here were produced by municipal officials in

Santiago de Guatemala (Antigua) in the aftermath of the events of August-September of that year, and in response to demands by many of its residents that the city be relocated. Officials within the *cabildo*, or municipal government, themselves residents of long-standing, shared the view that in the light of the extent of the damage suffered by the city as a result of the recent earthquake, it was imperative to obtain the required formal royal approval to initiate the process of relocation. It was with this purpose in mind that the *cabildo* empowered *alcalde ordinario* Juan de Rubayo Morante to carry out investigations in the local area, to interview key witnesses, and to dispatch their testimonies, along with other evidence in support of their case, to Spain. The resulting file, comprising nearly 180 densely-written and bound pages, was entitled “*Autos Hechos Sobre el Lastimoso, Estrago y Ruina que Padecio esta Ciudad de Guatemala ...*” (henceforth, *Autos*), a copy of which is housed in the Archivo General de Centro América (AGCA) in Guatemala City.

Individual testimonies contained in the *Autos* describe a succession of natural disasters, beginning with a VEI 4 eruption (GVP) of Volcán de Fuego on August 27th and 28th of 1717 and culminating with a series of severe local earthquakes and major mudflows from Volcán de Agua in late September. Taken together, these testimonies represent a remarkable historical record of social and scientific significance. From a scientific perspective, they provide important insight into a rare example of triggered (cascading) hazards, where activity at one volcano triggers activity at a neighboring volcano. From a social science perspective, the (over-) reaction that prompted this interesting early example of hazard data collection derived explicitly from memories of the catastrophic (defining) event in 1541.

3. Methods

The *Autos* comprise 45 separate documents that record written and oral accounts provided by testimonies of 20 individuals, including municipal officials, eyewitnesses, and residents with experience of prior similar events. Given the motives that led to their production – namely, to support the *cabildo*’s case for relocation of the capital city – we address the issue of credibility at the outset (Leroy, 2006), specifically the possibility the experience, impact and consequences of the events that took place in 1717 may have

been exaggerated for the purpose of enhancing the case for relocation. The similarity between the accounts that discuss the timing and nature of the activity leads us to conclude, however, that this bias did not affect the accuracy of reporting in this regard. At the same time, we are interested in the witness bias from the perspective of assessing the ways in which the response of the community was affected by the longer history of prior damaging events, and most particularly by the memory of the disaster that destroyed the original city of Santiago de los Caballeros in 1541.

Extracting specific geologic information from the *Autos* required first reading and translating the accounts, and then a second translation from the descriptive original language to modern geologic terminology. The formulaic nature of the process of evidence-gathering – a characteristic of Spanish colonial judicial processes – enables us to place the witnesses in specific locations at the time the events they describe occurred, and to record these in a GIS database, which in turn allows us to assess the spatial as well as temporal reach of the events experienced (Fig. 3). Other testimonies provide information about events witnessed from afar, or told to the witness by someone else. Testimonies by witnesses who traveled extensively to collect data are attached to multiple locations on the maps. Each testimony was then reviewed for (1) geologic information, (2) timing of events and (3) information about event impact. In the text below, we reference individual testimonies using the testimony number (T1, etc.), which is keyed to witness locations shown in Figure 3 and included in Table S1 (Supplementary Material).

4. Results

The *Autos* describe a sequence of natural events that began with a large eruption at Fuego on August 27-29, 1717, and ended with a destructive local earthquake on September 29 and subsequent south-traveling mudflows from Agua. Below we summarize observations from the *Autos* of the eruption, the subsequent geophysical activity, and the events of late September.

4.1 Eruption of Fuego, August 27-28, 1717

Eighteen of the documents in the *Autos* describe the eruption of Fuego. All concur that the eruption occurred on August 27th and 28th (e.g., T5), although some witnesses say

that it continued into August 29th (e.g., T7, T8 and T14). The first signs of activity were small ash pulses on the evening of August 27th (T14); the main phase started on the evening of August 27th (T11, T16, T34). For many of the witnesses, the first indications of activity were not visual, but instead were *estruendos* (crashing sounds) that were particularly loud later that evening (T8). By the following day, emitted ash obscured the daylight and witnesses described “rivers of fire” from the summit that contained variously sized rocks that traveled with so much force that they uprooted trees (T44). We interpret these to be pyroclastic flows produced by collapse of advancing lava flows, as seen in 1974 (Rose et al., 1978).

Predictably, accounts of the activity vary with witness location (Fig. 4). Witnesses who were relatively close to the volcano (T1, T34, T44) focused on the plume that reached “high” into the air, starting on August 27th. They also described *estruendos*, *retumbos* (rumbles), *temblores* (tremors), and shaking of the ground during the eruptive activity (T1, T5, T34). In Santiago de Guatemala, it was claimed that the eruption deposited so much ash that people had to cover their eyes to walk through the streets (T34). Witnesses in the capital city also reported that the ‘fire’ from the volcano could be seen at night from <40 (T17) to >100 leagues (222 – 556 km) away (T44). Confirmation comes from a witness in San Miguel (El Salvador; located approximately 50 leagues from Santiago de Guatemala), who reported tall *llamas* (flames) of fire on the night of August 28th (T11). *Retumbos* were also heard at great distances from the volcano, as reported by the two witnesses in El Salvador, who either ‘experienced’ (T13) or ‘heard’ (T11) *retumbos* during August 27-28 eruptive activity.

Direct damage from the eruption was worst in the valley between Fuego and Agua, including the pueblos of Siquinala, Santa Lucia, and Alotenango (T26). Although the *vecinos* (inhabitants) of Santiago de Guatemala were not directly affected by the eruption, many were terrified by the combination of the fire, rocks, smoke and ash:

“... Que es cierto ... que los terremotos y otros graves perjuicios, que se han experimentado en esta ciudad, provienen de los volcanes inmediatos a ella, como se ha experimentado en muchas ocasiones, y especialmente la noche del día veinte y siete de Agosto pasado de este presente año, y el día

siguiente en que el uno de ellos abortó voraces lenguas de fuego y humo, cuyo estruendo aterrizó a todos los habitantes de esta ciudad...”

“It is true ... that the earthquakes and other serious afflictions that have been experienced in this city, derive from the volcanoes which lie nearby, as has been experienced on many occasions, and especially on the night of 27 August of this year and the following day when one of these aborted voracious tongues of fire and smoke, making crashing sounds that terrorized all of the inhabitants of this city.”

(T5)

4.2 Post-eruptive activity – August 29 – September 29, 1717

During, and for at least 33 days following, the eruption of Fuego on August 27th, the volcano showed signs of unrest, particularly in the form of both *retumbos* and *temblores* (T1, T8, T14, T44). According to accounts in the *Autos*, *retumbos* were primarily heard (T5, T10), although in some instances they were also felt (T1, T14); the *temblores* often mentioned in the same context were always felt (ground shaking). Witnesses in proximal locations insisted that both were from sources near (T10), or even “inside” (T5), the volcano.

During the same period, the *Autos* also provide numerous descriptions of ground fissures, or *barrancas* (ravines), that increased from meters to tens to hundreds of meters in width and depth (T2, T5, T14, T15). It is unclear from the accounts whether these fissures formed during, or shortly after, the August 27-28 eruption. At the same time a *brecha* (breach) opened on Fuego from the summit to the east (toward Alotenango; T5, T7, T17):

“... con la ocasión del reconocimiento que hizo del dicho Volcán de Fuego, temiendo el que sus piedras no atajasen el dicho rio desagüe de esta ciudad y de dichas haciendas, subió parte de el arriba como hasta más que medio volcán, y vio una barranca que corre a la cima para abajo, tan profunda que le causó terror y miedo, que al parecer tendrá como hasta

cien varas de hondura, y de ancho como media cuadra, la cual le dijo un indio que llevaba en su compañía que era nuevamente abierta con la ocasión del fuego que había echado porque antes de él solo era una pequeña barranquilla de vara y media de hondo, por donde con facilidad bajaban y conducían madera...”

“...at the time of the survey of Volcán de Fuego which he conducted, [and] fearing that the rocks might block the river drainage of this city and [surrounding] haciendas, he climbed more than half-way up the volcano and saw a ravine that ran from the summit downwards, so deep that [on seeing it] he felt terror and fear. It appears to be up to 100 varas in depth [~83m], and about a half cuadra in width [125m], and according to an Indian who accompanied him, it had opened recently, at the same time as the fire spewed [by the volcano], because previously it was only a shallow ravine, 1.5 varas in depth, down which they comfortably transported wood...”

(T5)

This witness also noted that the *barranca* must have carried a large current of water because of the branches and trees that it had transported to the river. Other witnesses claimed that another *barranca* had formed from the volcano's summit to the south (T14, T17), and that additional openings produced smoke or steam, and emanated heat and a stench that made people ill (T14, T15).

During the same period, seven of the accounts in *Autos* describe an unusual sensation that they felt when traveling near the volcano, which they likened to walking on hollow ground, or the way the ground sounds when horses or carriages were in motion (T1, T7, T14, T17, T29, T44). A report from the eastern slopes of Fuego (T15) recounts more specifically the sensation that a subterranean *bóveda* (cellar) existed beneath the volcano:

“...y que ...las cabalgaduras ... con su piso parecía pisaban sobre una bóveda y así mismo vieron salir algún humo del centro de dicho barranca como de unos ronroneos expeliendo tanto calor y hedor...”

“...And .. it appeared [to those] on horseback that with each step they were treading over a vault and they also saw some steam rise from the said ravine, like purrs releasing a lot of heat and odor...”

Importantly, this account links the sensation of hollow ground directly to the formation of a *barranca* that was releasing both heat and pungent steam.

4.3 Earthquake of September 29, 1717

On the evening of September 29, 1717, several large earthquakes destroyed much of Santiago de Guatemala and the surrounding pueblos, and took many lives (T1). The earthquakes clearly had a local origin (T10, T11, T13, T18), although they were also felt on the Costa de Escuintla (then called Costa de Esquintlapeque), about 70 km south of Santiago de Guatemala (Fig. 4). Critically, all witnesses (T5, T14, T15) were convinced that the earthquakes were caused by the volcanoes:

“...Y que el asentar que dichos terremotos provienen de los volcanes es porque tiene el declarante su residencia en las haciendas que fueron del Capitán Don Joseph de Castillo, que están casi en la falda del Volcán de Fuego por un lado, y por el otro lado con inmediatez al de Agua, y por ello hallándose en el campo le cogieron dichos terremotos, en el, los cuales sintió con imponderable fuerza, o estrépito, y tal que fue preciso arrodillado acercarse de un palo para poderse mantener, y como estaba en la frente del dicho Volcán de Fuego, sintió que el ruido y fuerza de los terremotos salían de él, cuya presunción le confirman los retumbos que hacen mover la tierra porque los oye en el dicho volcán, el que tiene profundas barrancas, o abras recientes...”

“... Because the witness resides in the haciendas ... which on one side extend almost to the slopes of Volcán de Fuego, and on the other lie close to [Volcán] de Agua, he can assert that said earthquakes come from the volcanoes ... he found himself in his fields when the earthquakes struck, with such strength ... that, kneeling, he had to lean on a stick to steady himself. And as he was in front of Volcán de Fuego, he felt that the noise and force of the earthquakes came from it [the volcano]. His assumption is confirmed by the retumbos that make the earth move, because he hears them in said volcano [Fuego] which has [formed] new deep barrancas or openings...”

(T5)

The interpretation of a local source is supported by the severe damage reported in Alotenango and Ciudad Vieja, which lie between, and close to, both volcanoes (T10, T12, T29; Fig. 4). The earthquakes also caused significant damage within Santiago de Guatemala - one eyewitness estimated that the earthquake destroyed half the city (T31) – although here the bias of the witnesses would tend to exaggerate the impacts. That said, one account provides a detailed and specific list of the damages to important religious and government buildings (T32).

4.4 Mudflow from Volcán de Agua, September 29, 1717

The impact of the September 29 earthquakes was compounded by mudflows from Agua that were apparently triggered by the seismic activity. The flows originated high on the southwest slopes of the volcano and travelled south, away from the primary population centers, and, it was said, eventually reached the ocean (Fig. 5). Not surprisingly, the pueblos Masagua and Mistlan on the Rio Guacalate were most impacted by the mudflows (T12). The most detailed description of the source of the mudflows comes from a witness from the pueblo of Esquintlapecque (T23). He was ‘four leagues’ up the slopes of Volcán de Agua when the flows prevented him from continuing, so he climbed a small hill to get a better view. He describes three separate flows from upslope that first combined, and then split, around the high point where he was standing. The two

resulting flows eventually merged into a single flow south and downslope from his location (Fig. 6) and continued down the southwest flank of the volcano to join the Rio Guacalate near Escuintla. This account provides the critical observation that the flows originated from new ‘*abras*’ (openings) on the upper slopes of the volcano that hadn’t been there before; for this reason the witnesses attributed the flows directly to the September 29th earthquake (e.g., T12).

Several witnesses assert that the mudflow moved with great force and was very large, and that it carried sizeable sticks and rocks that were deposited along its path (T12, T15, T21). In this it sounds like a ‘normal’ debris flow. However, some witnesses also noted that the mudflows had unusual properties: they were yellow, they had a distinctive and repugnant sulphurous smell, and they were hot enough to kill all of the fish in the river (T14, T15, T17, T18, T19, T21, T22, T25, T36, T39, T44). These descriptions demonstrate that, in both their source and their character, the mudflows of September 29-30 were different from typical rainfall-triggered mudflows at Agua, which originate at the volcano’s summit and travel north toward Ciudad Vieja.

Retumbos were also heard during the mudflows (T14). This association led witnesses to relate the September 29 earthquakes, the mudflows, and activity of both volcanoes:

“...y que los retumbos que hacen mover la tierra y se continúan hasta hoy los tiene causados del dicho volcán, por la dicha razón de la inmediación con que está la casa de su habitación, y así por esto como por las abras que tiene dicho volcán de agua y la que por ellas se dice ha arrojado así a la banda del sur...”

“...And that the retumbos that make the earth move and which continue to this day are caused by the said volcano [which he knows] because the house in which he lives is near to it and ... because of the openings that have appeared on Volcán de Agua and down which it has expelled [material] towards the south ...” (T10)

Additional tremors (T11) and mudflows (T22, T23) were reported in October, although clearly the peak of the activity was on September 29-30. These events prompted great concerns, particularly that Agua volcano would “entirely burst” and flood the city (T18); for this reason, two government officials were instructed to survey both volcanoes, while paying particular attention to Agua (reported in T19-T30). Of most concern to the citizens of Santiago de Guatemala was the possibility that additional disturbances to either Volcán de Agua or Volcán de Fuego could trigger a collapse from the slopes of one volcano that that would block the city’s only drainage, Rio de Magdalena. They also considered that if Agua experienced another mudflow of the same magnitude but directed to the north, it would “undoubtedly” inundate the city (T6, T7, T8).

5. Discussion

As described above, the *Autos* provide detailed spatial and temporal information about the cascading hazards that commenced with the late August awakening of Volcán de Fuego and ended with the damaging local earthquake and mudflows from Volcán de Agua. They also provide important insight into the (mis)perceptions of some of the population about the nature of those hazards and their potential impact on the capital city. Here we first provide a geologic interpretation of the volcanic activity, the subsequent earthquakes and the culminating mudflows from Volcán de Agua. We then examine the local response to these events, particularly the perception of the people of Santiago de Guatemala that their city was in an unsafe location.

5.1 Interpretation of the events of August-September 1717

The evidence provided above supports previous interpretations of the August 27-29, 1717 eruption as a VEI 4 event (GVP), particularly when compared with detailed descriptions of the most recent VEI 4 eruption in 1974 (Rose et al., 1978). Similarities between the two eruptions include the small precursory episodes of ash release, the high ash plumes that characterized the peak activity, and the accompanying ‘rivers of fire’ (pyroclastic flows). Eruptive activity in 1717 appears, however, to have peaked more quickly (between August 27 and 29), and decayed more rapidly, than the 1974 activity, which continued for two weeks. Another similarity is the formation of numerous hot and

steaming *abras* (openings, fissures) on the volcano's flanks. In 1717, fissures appeared on both the south flank and on the east flank (toward Agua). In 1974, a dominant structural trend was identified along a NNE-SSW axis, while a weakness to the east was suggested by microseismicity trends after the 1974 activity (Rose et al., 1978).

Importantly, near-surface magma migration continued after the end of the visible eruption. Evidence for continued magmatic activity includes both the numerous reported *retumbos* (heard) and *temblores* (felt) earthquakes in September, as well as descriptions of barrancas and 'hollow ground' in the region between Fuego and Agua (Fig. 3). Together, these data suggest that subsurface magma intrusion may have created both surface and near-surface openings, perhaps caused by extension above a propagating dyke. Similarly, the several months of microseismicity recorded after the 1974 Volcán de Fuego eruption were interpreted to result from continued activity of the dike-like conduit responsible for feeding the eruptive activity.

The post-eruption unrest culminated in a strong earthquake on September 29, 1717. Testimonies in the *Autos* unambiguously demonstrate that this was a local, not a regional, earthquake. Moreover, although the earthquake clearly affected parts of the capital city Santiago de Guatemala and was felt to a lesser degree along the Costa de Escuintla (over 70 km to the south), the earthquake was felt most intensely in Alotenango and Ciudad Vieja (that is between Volcán de Agua and Volcán de Fuego; T5; Fig. 4). In fact, some testimonies state explicitly that the earthquake was hardly experienced outside of those towns (e.g., T10), and that the towns most severely affected were those on the slopes of Volcán de Agua (T12). This pattern of impact strongly suggests that the earthquake was caused by faulting related to magma intrusion along a fissure or dyke system propagating east from Volcán de Fuego toward Volcán de Agua, consistent with evidence for eastward propagating dykes during the month of September.

Further evidence for lateral magma propagation lies in the mudflows, which several witnesses thought were triggered by the seismic activity. Evidence for triggering includes emanation of the mudflows from new *abras* on the SW flanks of the volcano (Fig. 6), and descriptions of steaming *avenidas* of water and yellow mud that smelled of sulphur, both of which suggest involvement of a hydrothermal system within Agua's edifice. The mudflows were also accompanied by *estruendos* (crashing, or exploding

sounds), which suggests that small phreatic explosions may have occurred in conjunction with vent formation. These observations, together with the absence of reports of heavy rain, show that the mudflows were not generated by excessive rainfall, but instead by groundwater emerging from within the volcano. Taken together, we conclude that there is overwhelming evidence that a magmatic intrusion from Fuego (probably in the form of a dyke) triggered both the September 29 earthquake and the mudflows from Agua.

5.2 Other examples of cascading volcano hazards involving hydrothermal systems

Magma-induced changes in subsurface hydrologic systems are not uncommon. Manifestations of such changes include phreatic (steam-driven) explosions, changes in hydrothermal systems, groundwater-triggered mudflows and elevated fluxes in local rivers (e.g., Gadow, 1930; Roobol and Smith, 1975; Witze and Kanipe, 2014) or even large landslides (e.g., Voight *et al.*, 1981, 1983; Siebert, 2002). Less common, although not unheard of, is disturbance of a hydrothermal system in one volcano by magmatic activity at a neighboring volcano. Perhaps the most dramatic example of such triggered activity is provided by the 1792 eruption of Unzen volcano, Japan (e.g., Siebert *et al.*, 1987; Siebert, 2002).

Mount Unzen is a volcanic complex that includes the active peak – Fugen-dake – and an older (dormant) peak, the Mayu-yama dome. Fugen-dake erupted on February 10, 1792, after three months of precursory seismicity and phreatic eruptions. Explosive activity gave way to lava flows on March 1; by late April, seismic activity (both felt and heard) propagated to Mayu-yama, 5 km to the east. An earthquake on April 29 caused the dome to slide 200m, and prompted evacuation of the local population. Three weeks later, on May 21, two strong earthquakes triggered a debris avalanche from Mayu-yama that traveled to the sea; the resulting tsunami killed ~15,000 people, making it the most devastating volcanic disaster in Japanese history (e.g., Siebert *et al.*, 1987). In the weeks following the collapse, hot water continued to flow from the scarp, consistent with release of a pressurized hydrothermal system (Siebert, 2002).

The collapse of Mayu-yama dome was probably caused by saturation of the volcanic edifice as hydrothermal waters migrated in front of advancing magma. We suggest a similar scenario for the 1717 mudflows from Agua volcano. As in Japan, both

seismic activity and fissure formation provide evidence of subterranean magma migration between the late August Fuego eruption and the late September earthquakes and mudflows from Agua. Also similar is the emission of over-pressured water (sufficient to form new outlets on the flanks of Agua) from a hydrothermal system (evidenced by the temperature, color and smell of the mud). Importantly, this event was sufficiently unusual that it must have added to the anxiety of the local communities, who were already stressed by the rather severe eruption and the 33 days of subsequent unrest.

5.3 The long shadow of 1541

The events of August-September 1717, although clearly disruptive, were not catastrophic, or even disastrous. Citizens of the area had been living with frequent volcanic and seismic activity since the time of settlement, and some recognized the links between these geophysical events (T36). Why, then, did these events prompt a call from many of the inhabitants of Santiago de Guatemala to relocate the capital city farther away from Volcán de Agua? We address this question by first reviewing the types of information provided by the eyewitnesses and municipal officials regarding previous destructive events related to both eruptions from Fuego and regional seismic activity. We then focus on the specific nature of threats posed by Agua, particularly when placed in the context of the catastrophic 1541 debris avalanche and mudflow.

Volcán de Fuego is frequently active, and has been since the Spanish conquest; in fact, Fuego may have been erupting when the Spanish first arrived in the region (Restall and Asselbergs, 2007). The *Autos* demonstrate that the residents of the area were very familiar with Fuego's eruptive history. For example, witnesses T7 and T8 explicitly mention eruptions earlier in the century, and municipal officials recognize that much of the land was "made by volcanoes" (T17). More importantly, official reports about the 1717 events also include copies of reports made after the 1705 Fuego eruption, with descriptions of the "exceptional quantity of sand and ash that obscured the sun and the daylight", and the statement that more residents of Guatemala have been killed by "fuegos del volcán" than died from human conflict (T46).

Several of the testimonies in the *Autos* also relate to seismic activity. One witness (T17) states that the city of Santiago de Guatemala had to be rebuilt three times since the

16th century because of numerous eruptions and earthquakes, and another (T30) notes that the terrain is ‘sandy’ (covered with volcanic ash) and therefore unstable. Accounts documenting damage caused by the earthquake of September 29 include descriptions of the unusual places where Mass was being celebrated because of damage to churches (T2, T30), the total destruction of Alotenango (T29), the estimated costs of rebuilding Santiago de Guatemala (T32, T41), the decline in taxes collected (T40, T46) and the prominent families who, in December 1717, were still living on the streets because of earthquake damage and fear of further tremors (T37, T44). These statements provide the sound economic argument for relocating the city farther away from the “pernicious” and “nearby enemy volcanoes”.

It is clear from the *Autos*, however, that the mudflows from Agua were considered not only unusual but terrifying. Moreover, the testimonies show that the fears provoked by the mudflows were inflated relative to the actual hazard, and were deeply rooted in memories of the devastating mudflows that destroyed the original capital city in 1541. The 1541 event is specifically invoked by three accounts in the *Autos* (T6, T36, T44), all of which refer to the >600 casualties from that event. Importantly, it is clear that this information was transmitted in both written and form, the latter of which is documented by T36, which are extracts from a book written in 1714 by Fray Francisco Vasquez, a Franciscan friar and historian. In the book he reviews natural disasters that had affected the city since its founding, beginning with the “fatal flood” of 1541. In his description of the event he emphasized the heavy hurricane-generated rainfall that preceded the 1541 mudflows, as well as the terrible noises and ground shaking that accompanied the collapse. Several other witnesses (T6, T7, T8, T10, T12, T13, T15, T16, T18, T21) do not refer specifically to the events of 1541, but did express fears of inundation during the night of September 29. More specifically, witnesses worried about spontaneous generation of mudflows from the flanks of Agua, and consequent blockage of the only drainage from the city (Rio de Magdalena), which ran between the two volcanoes (Fuego and Agua). These fears prompted many to consider moving farther from the volcanoes (T8, T12, T16, T17) and underpinned the consensus of a public meeting on October 20 to request permission to relocate the capital city (T42).

5.4 *Social memory and hazard perception*

The critical importance of the 1541 events in the community interpretation of, and response to, the cascading hazards of August-September 1717 provides a clear example of ‘social memory’ (McIntosh et al., 2000) and the role of past events in determining what is perceived to be a disaster (Slovic, 2000; Bankoff, 2004; Perez, 2001). The time frame of community memory and vulnerability has been recognized (e.g., Oliver-Smith 1986; 2002; Bankoff, 2004) but commonly does not find a place within theoretical frameworks of disaster and change (e.g., Birkmann et al., 2010). This omission reflects (1) recent theoretical advances in disaster studies, which focus on either modern disasters or catastrophic collapse of ancient empires, neither of which provide the time resolution required for studies of the impacts of social memories (e.g., Diamond and Robinson 2010; Cooper et al., 2012); (2) the limited number of historical studies of regions prone to repeated events (e.g., Chester et al., 2012); and (3) neglect, until recently, of social memories preserved within oral traditions (e.g., Masse et al., 2007; Cronin and Cashman 2008; Cashman and Cronin, 2008; Cashman and Giordano, 2008 and references therein).

The 1717 example also shows the power of social memory to drive hazard mitigation. Population displacement (migration) has been a common response to recent disastrous events (Witham, 2005); it also represents an effective long-term strategy for coping with hazards (Riede, 2014). From this perspective, we can view the inhabitants of Santiago de Guatemala as engaging in a response driven not by irrational fears or misperceptions of the actual hazards, but by attempts to employ a rational strategy to reduce their vulnerability to future events. That they are attempting to do this within the restrictions imposed by a colonial structure – restrictions that required extensive evidence-based documentation of the natural events and their impacts – provides a unique window into the workings of social memory in a pre-industrial and semi-autonomous community.

The *Autos* also provide an example of an early systematic survey of both a cascade of hazardous events and their impact. The *Autos* are systematic in the formulaic structure of each testimony, which imposes uniformity on eyewitness data collection that presages the format of social science surveys developed more than three centuries later. Of critical importance to our study are data related to the position of each witness, and

the extent to which the accounts are based on first hand observations or second hand consultation of eyewitnesses. Also interesting is the application of scientific methods to establish, for example, the local origin of the September 29 earthquake, which they did by soliciting accounts from both local and distant (El Salvador) observers. The *Autos* thus provide systematic documentation of hazardous events and their impacts for the purpose of improving both scientific understanding and resilience in the face of future events.

6. Summary and Conclusions

Here we have demonstrated ways in which Spanish archival sources provide key information about both the physical nature of a cascading sequence of natural hazards and a long-term cascade of responses triggered by memories of an early catastrophic event. We have also shown that documentation of the 1717 activity in the form of the *Autos* is unusual from the perspective of natural hazard studies, in that it provides an early example of both a systematic survey of the physical nature and impact of a complex sequence of natural events, as well as a social science survey of human responses to this activity.

The scientific importance of the events of 1717 lies in the clear evidence that magmatic (and associated seismic) activity at Fuego triggered a disturbance of the hydrothermal system at neighbouring Agua. Although not unprecedented (e.g., Siebert et al., 1987), remote triggering of hydrothermal activity is unusual, and raises important questions about hazard assessment of apparently dormant volcanoes such as Agua (e.g., Schilling et al., 2001). Our interpretation of a cascading sequence of hazards transferred from Fuego to Agua also provides a new and integrated perspective of these events. This integrated view contrasts with previous geologic and historic interpretations of the 1717 activity, which consider, separately, the volcanic (e.g., Vallance et al., 2001; Martin and Rose, 1981), seismic (e.g., Feldman, 1993) and hydrologic (e.g., Schilling et al., 2001) events. More broadly, our analysis places the August-September, 1717, activity at Fuego and Agua within a larger framework of volcano-triggered hydrologic hazards that include the under-appreciated hazard posed by interactions between volcanic systems.

The historical importance of this work, from a scientific perspective, lies in the systematic eyewitness accounts assembled in the *Autos*. Organized scientific responses to

volcanic eruptions can be dated to the 1883 eruption of Krakatau, which was followed by detailed studies of both regional and global impacts of the event (e.g., Simkin and Fiske, 1983). Modern social science studies of natural hazards, in contrast, start with seminal work in the 1960s that was summarized by Burton et al. (1978). From this perspective, the *Autos* represent a surprisingly detailed response to a series of cascading natural hazards, particularly given the low physical impact of the events (they did not create a natural disaster). From the ‘long shadow’ perspective, the key observation is that this response – systematic collection of witness accounts from a broad geographic region – can be linked directly to the still-vivid memories of a catastrophic mudflow 176 years earlier. The strength of these memories, as demonstrated by the extremity of the response (a plea by many citizens to relocate the capital city), not only supports Slovic’s (2000) emphasis on memorability as a key element of risk perception, but also shows the potential complexity of responses of past societies to hazardous events. This view supports the idea that natural disasters may be viewed as both historical processes and sequential events (Bankoff, 2004).

Finally, this research also illustrates the limitations of working with archival data. Although the witness accounts provide valuable (and often thoughtful) geologic observations, the descriptions are qualitative and of varying detail. In part this derives from their historical context, and the lack of formal scientific nomenclature for the events described. The language is descriptive and often metaphorical, and thus requires (necessarily subjective) translation into modern scientific language. Additionally, information gleaned from historical sources requires detailed contextual knowledge of the source. In the case of the *Autos*, the critical context is that these witness accounts were collected for the express intent of providing documentation for the Spanish government to support the municipal government’s request to relocate the capital city, which raises the concern that the accounts may be exaggerated. Surprisingly, however, this does not seem to have compromised the veracity of the observations of the events themselves. Moreover, this context likely encouraged the witnesses to include key historical details (about past eruptions, earthquakes and mudflows) that help to explain what appears, initially, to be an extreme over-reaction to a moderate eruption and strong, but not unprecedented, earthquakes and mudflows.

In summary, recent studies have shown the importance of employing the “usable past” (Stump, 2013) to provide immediacy to both hazard forecast scenarios and evidence-based policy recommendations (Reide, 2014). The mudflows from Agua that were triggered by magmatic activity at Fuego provide such an example, and suggest the importance of assessing volcanic hazard from regional, as well as the more typical single-volcano, perspectives. At the same time, this work illustrates the role of memory in risk perception. Understanding communal memories is crucial not only for effective risk communication and improved resilience, but also for inferring causal relationships between hazardous events and apparent responses in historical and archaeological records.

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Figure Captions

Figure 1 Location map showing the three capital cities of Guatemala and the nearby volcanoes. The cities are currently known as Ciudad Vieja (formerly Santiago de los Caballeros, founded in 1527), Antigua (formerly Santiago de Guatemala, relocated in 1542), and Guatemala City (relocated in 1773 following a large regional earthquake). The volcanoes Atitlan, Fuego, Agua and Pacaya lie along the Central America volcanic arc. All have been active during historical times except Agua.

Figure 2 Eruptive history of Fuego volcano since 1524, when the Spanish first arrived in the area. Data are from the Smithsonian Global Volcanism Program database [<http://www.volcano.si.edu/>] and provide a measure of the eruption size using the Volcano Explosivity Index [<http://volcanoes.usgs.gov/images/pglossary/vei.php>]. VEI 4 eruptions of 1717 and 1974 are highlighted, as is the only other VEI 4 eruption between 1524 and 1717, in 1581.

Figure 3 Map showing the approximate location of witness testimonies. Where the witnesses traveled to survey the effects of the different events, they are placed in all relevant locations. See Table S1 (Supplementary Material) for details.

Figure 4 Map showing the witness locations and inferred intensity (yellow, low intensity to orange, high intensity) of the September 29, 1717 earthquake. Key is the evidence from witnesses in El Salvador that they did not feel this event, which means that it was local. Also important is the evidence that the damage was most severe in Alotenango, which lies between the two volcanoes.

Figure 5 Map showing the witness locations and inferred intensity (pale green, low intensity to blue, high intensity) of the September 29 mudflows from Agua. Importantly these flows emanated from the southwest slopes of Agua and traveled south, and thus did not affect the capital city.

Figure 6 Sketch map from the Autos showing the new bocas formed on the flanks of Agua that fed the September 29 mudflows (from witness T23). The witness shows the flows merging upslope of him, splitting around high ground and converging down slope; the flow eventually fed into the Rio Guacalate near Escuintla.

The 1717 Eruption of Volcán de Fuego, Guatemala: Cascading Hazards and Societal Response

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Abstract

Assessing and communicating the risks posed by natural hazards requires not only a thorough understanding of the hazards but also an understanding of the spatial and temporal impact of successive events from the same source(s). This 4 dimensional approach requires the lens of time, which is often missing from modern responses to recent hazards, but also details of the event chronology and immediate human impact, which must be inferred from archaeological studies. Here we provide an example to illustrate the use of historical documents to fill this gap. We focus on the volcanically and seismically active region that hosts the capital city of Guatemala, which has been relocated twice in response to hazardous events since its original founding in 1524. More specifically, we examine documents, entitled “*Autos Hechos Sobre el Lastimoso, Estrago y Ruina que Padecio esta Ciudad de Guatemala ...*” [Autos] that were collected in response to a cascading sequence of volcanic, seismic and mudflow events in 1717 to support a request to the Spanish government to relocate the second capital city. These documents provide exceptional detail about the location of the witnesses, the nature of the hazardous activity and the response of local communities to individual events. This detail allows us not only to reconstruct the sequence of events but also to link volcanic activity at Volcán de Fuego to both local seismicity and mudflows from Volcán de Agua, which we interpret as triggered by intruding magma from Fuego. Additionally, the long and well documented history of the region shows how a single catastrophic event – in this case a large rainfall-triggered debris flow from Agua in 1541, which destroyed the first capital city – can reverberate through the centuries and affect the response of the local community almost 200 years later, in 1717, even though the origin and affected area of the mudflow hazard was very different in the two cases. This example thus illustrates the

importance of “memorability” in both the perception of, and response to, hazardous events (e.g., Slovic, 2000).

1. Introduction

Recent volcanic eruptions, such as that of Eyjafjallajökull volcano in Iceland in 2010, have stimulated important interactions among scientists, social scientists and emergency managers. However, such studies of recent events tend naturally to focus on immediate impacts, with the result that hazard management aims to improve immediate physical impacts of hazard (*vulnerability*), often at the expense of developing long-term (and sustainable) strategies for hazard mitigation (*resilience*; e.g., White et al., 2001). This approach, however, ignores the ‘long shadow’ (e.g., Grattan and Torrence, 2007) of such disasters, where ‘long’ refers to time scales relevant for either political or cultural change (e.g., Birkmann et al., 2010; Diamond and Robinson, 2010). A long view is provided, in contrast, by archaeological studies of the impact of past volcanic disasters on human societies (e.g., Sheets and Grayson, 1979). A challenge to archaeological studies, however, is causality must be assumed rather than proven (Coombes and Barber 2005; Leroy 2006). The time gap between archaeological and present day research is the realm of history, which can contribute robust chronologies that allow cause and effect to be linked (e.g., Vittori et al., 2007).

Here we use the historical record of Spanish colonial Guatemala to improve fundamental understanding of volcano-related hazards in the region, and to examine the role of past events on the response of the local population to an unusual cascading sequence of hazards in August and September of 1717. The written record of the area is extensive, because the events of interest occurred near the second location of the capital city of Guatemala, Santiago de Guatemala (now known as Antigua; Fig. 1), which lies close to the active Volcán de Fuego and dormant Volcán de Agua. Importantly, the first capital city – Santiago de los Caballeros – was destroyed by a disastrous mudflow from nearby Volcán de Agua in 1541, only 17 years after it was founded. The immediate consequence was relocation of the city to higher ground; the much more profound, and longer lasting, consequence was not only extended scientific debate about the mudflow origin (e.g., Maudsley, 1899; Anderson, 1908; Carmak, 1973), but also the extent to

which the destruction of Santiago de los Caballeros still looms large in the minds of local inhabitants. Here we examine the impact of the 1541 mudflow as viewed through the lens of a cascading sequence of hazardous events involving both Volcán de Agua and neighboring Volcán de Fuego in 1717 almost two centuries later, events that prompted local citizens to demand relocation of the capital city for a second time.

2. Background

It is well known that disastrous events can act as natural experiments (Diamond and Robinson, 2010) and/or catalysts of change (e.g., Burby et al., 2000; Perez, 2001; Birkmann et al., 2010). Change may occur by migration (abandoning the hazardous location) or adaptation, such as risk-based land use planning. To be effective, such planning must balance the benefits, as well as the drawbacks, of living in hazardous areas (e.g., White et al. 2001; Glavovic et al., 2010), and engage both community members and government officials (e.g., Cronin et al., 2004; Cashman and Cronin, 2008; Ricci et al., 2013). A key factor that affects community perceptions of risk is the *memorability* (and imaginability) of individual hazards (e.g., Slovic, 2000), such that an event that is memorable within the community for its real *or perceived* impact will be weighted more heavily in planning decisions than an event that is not as easily imagined. A modern example is the 1979 Three Mile Island nuclear accident and the effect of that accident on perceptions of risk related to nuclear power (e.g., Slovic et al., 1982; Kasperson et al., 1988). A different perspective on memorability can be found in studies of oral traditions. When stories must be passed orally from generation to generation, a community disaster may become “a defining experience that passes into shared memory” (Perez, 2001). In this way, inherited stories, whether oral or written, are often preserved where the knowledge contained is critical to community survival (e.g., Barber and Barber, 2006), and thus may critically influence community planning of future generations.

The long history (~ 300 years) of Spanish occupation of the area around Volcán de Fuego [Fuego] and neighboring Volcán de Agua [Agua] provides an unusual opportunity to evaluate both the behavior of the volcanoes and the communities that have grown up in their shadows. Both volcanoes form part of the central Guatemala arc (Fig. 1). Fuego has been one of the most persistently active of the Guatemalan volcanoes, with

57 confirmed eruptions, and several more unconfirmed, since the arrival of Spanish colonists in 1524 (Smithsonian Institute, Global Volcanism Program [GVP] database). Documentation of Fuego's activity is reasonably good because of its proximity to the original capital city of Santiago de los Caballeros, and to the relocated city of Santiago de Guatemala. Agua, in contrast, has no documented eruptions in the Holocene (Bonis and Salazar, 1973; Schilling et al., 2001; GVP). It has had, instead, numerous mudflows that have affected the area to the north of the volcano, including the area occupied by the first capital city (now Ciudad Vieja).

Fuego is basaltic andesite in composition, and most of its eruptions have been moderate in size and intensity (VEI 2 or 3; GVP). At the extremes are periods of persistent low level 'open vent' activity (Lyons et al., 2010), and larger (VEI 4) eruptions (Rose et al., 1978; Lyons et al., 2010; GVP). Recorded activity is episodic, with four 20-70 year periods of high activity accounting for 75% of the total (Fig. 2). Interestingly, this episodicity appears to be regional, such that activity at Fuego mirrors the rest of the Central American volcanoes (Martin and Rose, 1981). More importantly, by 1717, inhabitants of Santiago de Guatemala were very familiar with Fuego's range of volcanic activity.

Mudflows from Agua also vary in intensity, with the most severe being that of September 1541. The mudflow was caused by a debris flow that originated from the volcano's summit after unusually heavy rainfall. In this the event was similar to the devastating debris avalanche and resulting debris flow from dormant Casitas volcano, Nicaragua, in 1998, that was caused by intense rainfall associated with Hurricane Mitch (e.g., Schilling et al., 2001; Scott et al., 2005). The most recent mudflow to affect the area was caused by heavy rains associated with Tropical Storm Agatha in 2010. Much more unusual are mudflows that affect other sectors of the volcano. One such event occurred in September 1717, when mudflows associated with a large regional earthquake devastated areas on the southwest flank of the volcano. It is this event – both its cause and its impact on the local communities – that are the subject of this paper.

In 1717, Guatemala was part of the Spanish Empire; it was ruled by the Spanish monarch, but governed by a complex hierarchy of royal officials at the regional and local level. The historical sources that we analyze here were produced by municipal officials in

Santiago de Guatemala (Antigua) in the aftermath of the events of August-September of that year, and in response to demands by many of its residents that the city be relocated. Officials within the *cabildo*, or municipal government, themselves residents of long-standing, shared the view that in the light of the extent of the damage suffered by the city as a result of the recent earthquake, it was imperative to obtain the required formal royal approval to initiate the process of relocation. It was with this purpose in mind that the *cabildo* empowered *alcalde ordinario* Juan de Rubayo Morante to carry out investigations in the local area, to interview key witnesses, and to dispatch their testimonies, along with other evidence in support of their case, to Spain. The resulting file, comprising nearly 180 densely-written and bound pages, was entitled “*Autos Hechos Sobre el Lastimoso, Estrago y Ruina que Padecio esta Ciudad de Guatemala ...*” (henceforth, *Autos*), a copy of which is housed in the Archivo General de Centro América (AGCA) in Guatemala City.

Individual testimonies contained in the *Autos* describe a succession of natural disasters, beginning with a VEI 4 eruption (GVP) of Volcán de Fuego on August 27th and 28th of 1717 and culminating with a series of severe local earthquakes and major mudflows from Volcán de Agua in late September. Taken together, these testimonies represent a remarkable historical record of social and scientific significance. From a scientific perspective, they provide important insight into a rare example of triggered (cascading) hazards, where activity at one volcano triggers activity at a neighboring volcano. From a social science perspective, the (over-) reaction that prompted this interesting early example of hazard data collection derived explicitly from memories of the catastrophic (defining) event in 1541.

3. Methods

The *Autos* comprise 45 separate documents that record written and oral accounts provided by testimonies of 20 individuals, including municipal officials, eyewitnesses, and residents with experience of prior similar events. Given the motives that led to their production – namely, to support the *cabildo*’s case for relocation of the capital city – we address the issue of credibility at the outset (Leroy, 2006), specifically the possibility the experience, impact and consequences of the events that took place in 1717 may have

been exaggerated for the purpose of enhancing the case for relocation. The similarity between the accounts that discuss the timing and nature of the activity leads us to conclude, however, that this bias did not affect the accuracy of reporting in this regard. At the same time, we are interested in the witness bias from the perspective of assessing the ways in which the response of the community was affected by the longer history of prior damaging events, and most particularly by the memory of the disaster that destroyed the original city of Santiago de los Caballeros in 1541.

Extracting specific geologic information from the *Autos* required first reading and translating the accounts, and then a second translation from the descriptive original language to modern geologic terminology. The formulaic nature of the process of evidence-gathering – a characteristic of Spanish colonial judicial processes – enables us to place the witnesses in specific locations at the time the events they describe occurred, and to record these in a GIS database, which in turn allows us to assess the spatial as well as temporal reach of the events experienced (Fig. 3). Other testimonies provide information about events witnessed from afar, or told to the witness by someone else. Testimonies by witnesses who traveled extensively to collect data are attached to multiple locations on the maps. Each testimony was then reviewed for (1) geologic information, (2) timing of events and (3) information about event impact. In the text below, we reference individual testimonies using the testimony number (T1, etc.), which is keyed to witness locations shown in Figure 3 and included in Table S1 (Supplementary Material).

4. Results

The *Autos* describe a sequence of natural events that began with a large eruption at Fuego on August 27-29, 1717, and ended with a destructive local earthquake on September 29 and subsequent south-traveling mudflows from Agua. Below we summarize observations from the *Autos* of the eruption, the subsequent geophysical activity, and the events of late September.

4.1 Eruption of Fuego, August 27-28, 1717

Eighteen of the documents in the *Autos* describe the eruption of Fuego. All concur that the eruption occurred on August 27th and 28th (e.g., T5), although some witnesses say

that it continued into August 29th (e.g., T7, T8 and T14). The first signs of activity were small ash pulses on the evening of August 27th (T14); the main phase started on the evening of August 27th (T11, T16, T34). For many of the witnesses, the first indications of activity were not visual, but instead were *estruendos* (crashing sounds) that were particularly loud later that evening (T8). By the following day, emitted ash obscured the daylight and witnesses described “rivers of fire” from the summit that contained variously sized rocks that traveled with so much force that they uprooted trees (T44). We interpret these to be pyroclastic flows produced by collapse of advancing lava flows, as seen in 1974 (Rose et al., 1978).

Predictably, accounts of the activity vary with witness location (Fig. 4). Witnesses who were relatively close to the volcano (T1, T34, T44) focused on the plume that reached “high” into the air, starting on August 27th. They also described *estruendos*, *retumbos* (rumbles), *temblores* (tremors), and shaking of the ground during the eruptive activity (T1, T5, T34). In Santiago de Guatemala, it was claimed that the eruption deposited so much ash that people had to cover their eyes to walk through the streets (T34). Witnesses in the capital city also reported that the ‘fire’ from the volcano could be seen at night from <40 (T17) to >100 leagues (222 – 556 km) away (T44). Confirmation comes from a witness in San Miguel (El Salvador; located approximately 50 leagues from Santiago de Guatemala), who reported tall *llamas* (flames) of fire on the night of August 28th (T11). *Retumbos* were also heard at great distances from the volcano, as reported by the two witnesses in El Salvador, who either ‘experienced’ (T13) or ‘heard’ (T11) *retumbos* during August 27-28 eruptive activity.

Direct damage from the eruption was worst in the valley between Fuego and Agua, including the pueblos of Siquinala, Santa Lucia, and Alotenango (T26). Although the *vecinos* (inhabitants) of Santiago de Guatemala were not directly affected by the eruption, many were terrified by the combination of the fire, rocks, smoke and ash:

“... Que es cierto ... que los terremotos y otros graves perjuicios, que se han experimentado en esta ciudad, provienen de los volcanes inmediatos a ella, como se ha experimentado en muchas ocasiones, y especialmente la noche del día veinte y siete de Agosto pasado de este presente año, y el día

siguiente en que el uno de ellos abortó voraces lenguas de fuego y humo, cuyo estruendo aterrizó a todos los habitantes de esta ciudad...”

“It is true ... that the earthquakes and other serious afflictions that have been experienced in this city, derive from the volcanoes which lie nearby, as has been experienced on many occasions, and especially on the night of 27 August of this year and the following day when one of these aborted voracious tongues of fire and smoke, making crashing sounds that terrorized all of the inhabitants of this city.”

(T5)

4.2 Post-eruptive activity – August 29 – September 29, 1717

During, and for at least 33 days following, the eruption of Fuego on August 27th, the volcano showed signs of unrest, particularly in the form of both *retumbos* and *temblores* (T1, T8, T14, T44). According to accounts in the *Autos*, *retumbos* were primarily heard (T5, T10), although in some instances they were also felt (T1, T14); the *temblores* often mentioned in the same context were always felt (ground shaking). Witnesses in proximal locations insisted that both were from sources near (T10), or even “inside” (T5), the volcano.

During the same period, the *Autos* also provide numerous descriptions of ground fissures, or *barrancas* (ravines), that increased from meters to tens to hundreds of meters in width and depth (T2, T5, T14, T15). It is unclear from the accounts whether these fissures formed during, or shortly after, the August 27-28 eruption. At the same time a *brecha* (breach) opened on Fuego from the summit to the east (toward Alotenango; T5, T7, T17):

“... con la ocasión del reconocimiento que hizo del dicho Volcán de Fuego, temiendo el que sus piedras no atajasen el dicho rio desagüe de esta ciudad y de dichas haciendas, subió parte de el arriba como hasta más que medio volcán, y vio una barranca que corre a la cima para abajo, tan profunda que le causó terror y miedo, que al parecer tendrá como hasta

cien varas de hondura, y de ancho como media cuadra, la cual le dijo un indio que llevaba en su compañía que era nuevamente abierta con la ocasión del fuego que había echado porque antes de él solo era una pequeña barranquilla de vara y media de hondo, por donde con facilidad bajaban y conducían madera...”

“...at the time of the survey of Volcán de Fuego which he conducted, [and] fearing that the rocks might block the river drainage of this city and [surrounding] haciendas, he climbed more than half-way up the volcano and saw a ravine that ran from the summit downwards, so deep that [on seeing it] he felt terror and fear. It appears to be up to 100 varas in depth [~83m], and about a half cuadra in width [125m], and according to an Indian who accompanied him, it had opened recently, at the same time as the fire spewed [by the volcano], because previously it was only a shallow ravine, 1.5 varas in depth, down which they comfortably transported wood...”

(T5)

This witness also noted that the *barranca* must have carried a large current of water because of the branches and trees that it had transported to the river. Other witnesses claimed that another *barranca* had formed from the volcano's summit to the south (T14, T17), and that additional openings produced smoke or steam, and emanated heat and a stench that made people ill (T14, T15).

During the same period, seven of the accounts in *Autos* describe an unusual sensation that they felt when traveling near the volcano, which they likened to walking on hollow ground, or the way the ground sounds when horses or carriages were in motion (T1, T7, T14, T17, T29, T44). A report from the eastern slopes of Fuego (T15) recounts more specifically the sensation that a subterranean *bóveda* (cellar) existed beneath the volcano:

“...y que ...las cabalgaduras ... con su piso parecía pisaban sobre una bóveda y así mismo vieron salir algún humo del centro de dicho barranca como de unos ronroneos expeliendo tanto calor y hedor...”

“...And .. it appeared [to those] on horseback that with each step they were treading over a vault and they also saw some steam rise from the said ravine, like purrs releasing a lot of heat and odor...”

Importantly, this account links the sensation of hollow ground directly to the formation of a *barranca* that was releasing both heat and pungent steam.

4.3 Earthquake of September 29, 1717

On the evening of September 29, 1717, several large earthquakes destroyed much of Santiago de Guatemala and the surrounding pueblos, and took many lives (T1). The earthquakes clearly had a local origin (T10, T11, T13, T18), although they were also felt on the Costa de Escuintla (then called Costa de Esquintlapeque), about 70 km south of Santiago de Guatemala (Fig. 4). Critically, all witnesses (T5, T14, T15) were convinced that the earthquakes were caused by the volcanoes:

“...Y que el asentar que dichos terremotos provienen de los volcanes es porque tiene el declarante su residencia en las haciendas que fueron del Capitán Don Joseph de Castillo, que están casi en la falda del Volcán de Fuego por un lado, y por el otro lado con inmediación al de Agua, y por ello hallándose en el campo le cogieron dichos terremotos, en el, los cuales sintió con imponderable fuerza, o estrépito, y tal que fue preciso arrodillado acercarse de un palo para poderse mantener, y como estaba en la frente del dicho Volcán de Fuego, sintió que el ruido y fuerza de los terremotos salían de él, cuya presunción le confirman los retumbos que hacen mover la tierra porque los oye en el dicho volcán, el que tiene profundas barrancas, o abras recientes...”

“... Because the witness resides in the haciendas ... which on one side extend almost to the slopes of Volcán de Fuego, and on the other lie close to [Volcán] de Agua, he can assert that said earthquakes come from the volcanoes ... he found himself in his fields when the earthquakes struck, with such strength ... that, kneeling, he had to lean on a stick to steady himself. And as he was in front of Volcán de Fuego, he felt that the noise and force of the earthquakes came from it [the volcano]. His assumption is confirmed by the retumbos that make the earth move, because he hears them in said volcano [Fuego] which has [formed] new deep barrancas or openings...”

(T5)

The interpretation of a local source is supported by the severe damage reported in Alotenango and Ciudad Vieja, which lie between, and close to, both volcanoes (T10, T12, T29; Fig. 4). The earthquakes also caused significant damage within Santiago de Guatemala - one eyewitness estimated that the earthquake destroyed half the city (T31) – although here the bias of the witnesses would tend to exaggerate the impacts. That said, one account provides a detailed and specific list of the damages to important religious and government buildings (T32).

4.4 Mudflow from Volcán de Agua, September 29, 1717

The impact of the September 29 earthquakes was compounded by mudflows from Agua that were apparently triggered by the seismic activity. The flows originated high on the southwest slopes of the volcano and travelled south, away from the primary population centers, and, it was said, eventually reached the ocean (Fig. 5). Not surprisingly, the pueblos Masagua and Mistlan on the Rio Guacalate were most impacted by the mudflows (T12). The most detailed description of the source of the mudflows comes from a witness from the pueblo of Esquintlapecque (T23). He was ‘four leagues’ up the slopes of Volcán de Agua when the flows prevented him from continuing, so he climbed a small hill to get a better view. He describes three separate flows from upslope that first combined, and then split, around the high point where he was standing. The two

resulting flows eventually merged into a single flow south and downslope from his location (Fig. 6) and continued down the southwest flank of the volcano to join the Rio Guacalate near Escuintla. This account provides the critical observation that the flows originated from new ‘*abras*’ (openings) on the upper slopes of the volcano that hadn’t been there before; for this reason the witnesses attributed the flows directly to the September 29th earthquake (e.g., T12).

Several witnesses assert that the mudflow moved with great force and was very large, and that it carried sizeable sticks and rocks that were deposited along its path (T12, T15, T21). In this it sounds like a ‘normal’ debris flow. However, some witnesses also noted that the mudflows had unusual properties: they were yellow, they had a distinctive and repugnant sulphurous smell, and they were hot enough to kill all of the fish in the river (T14, T15, T17, T18, T19, T21, T22, T25, T36, T39, T44). These descriptions demonstrate that, in both their source and their character, the mudflows of September 29-30 were different from typical rainfall-triggered mudflows at Agua, which originate at the volcano’s summit and travel north toward Ciudad Vieja.

Retumbos were also heard during the mudflows (T14). This association led witnesses to relate the September 29 earthquakes, the mudflows, and activity of both volcanoes:

“...y que los retumbos que hacen mover la tierra y se continúan hasta hoy los tiene causados del dicho volcán, por la dicha razón de la inmediación con que está la casa de su habitación, y así por esto como por las abras que tiene dicho volcán de agua y la que por ellas se dice ha arrojado así a la banda del sur...”

“...And that the retumbos that make the earth move and which continue to this day are caused by the said volcano [which he knows] because the house in which he lives is near to it and ... because of the openings that have appeared on Volcán de Agua and down which it has expelled [material] towards the south ...” (T10)

Additional tremors (T11) and mudflows (T22, T23) were reported in October, although clearly the peak of the activity was on September 29-30. These events prompted great concerns, particularly that Agua volcano would “entirely burst” and flood the city (T18); for this reason, two government officials were instructed to survey both volcanoes, while paying particular attention to Agua (reported in T19-T30). Of most concern to the citizens of Santiago de Guatemala was the possibility that additional disturbances to either Volcán de Agua or Volcán de Fuego could trigger a collapse from the slopes of one volcano that that would block the city’s only drainage, Rio de Magdalena. They also considered that if Agua experienced another mudflow of the same magnitude but directed to the north, it would “undoubtedly” inundate the city (T6, T7, T8).

5. Discussion

As described above, the *Autos* provide detailed spatial and temporal information about the cascading hazards that commenced with the late August awakening of Volcán de Fuego and ended with the damaging local earthquake and mudflows from Volcán de Agua. They also provide important insight into the (mis)perceptions of some of the population about the nature of those hazards and their potential impact on the capital city. Here we first provide a geologic interpretation of the volcanic activity, the subsequent earthquakes and the culminating mudflows from Volcán de Agua. We then examine the local response to these events, particularly the perception of the people of Santiago de Guatemala that their city was in an unsafe location.

5.1 Interpretation of the events of August-September 1717

The evidence provided above supports previous interpretations of the August 27-29, 1717 eruption as a VEI 4 event (GVP), particularly when compared with detailed descriptions of the most recent VEI 4 eruption in 1974 (Rose et al., 1978). Similarities between the two eruptions include the small precursory episodes of ash release, the high ash plumes that characterized the peak activity, and the accompanying ‘rivers of fire’ (pyroclastic flows). Eruptive activity in 1717 appears, however, to have peaked more quickly (between August 27 and 29), and decayed more rapidly, than the 1974 activity, which continued for two weeks. Another similarity is the formation of numerous hot and

steaming *abras* (openings, fissures) on the volcano's flanks. In 1717, fissures appeared on both the south flank and on the east flank (toward Agua). In 1974, a dominant structural trend was identified along a NNE-SSW axis, while a weakness to the east was suggested by microseismicity trends after the 1974 activity (Rose et al., 1978).

Importantly, near-surface magma migration continued after the end of the visible eruption. Evidence for continued magmatic activity includes both the numerous reported *retumbos* (heard) and *temblores* (felt) earthquakes in September, as well as descriptions of barrancas and 'hollow ground' in the region between Fuego and Agua (Fig. 3). Together, these data suggest that subsurface magma intrusion may have created both surface and near-surface openings, perhaps caused by extension above a propagating dyke. Similarly, the several months of microseismicity recorded after the 1974 Volcán de Fuego eruption were interpreted to result from continued activity of the dike-like conduit responsible for feeding the eruptive activity.

The post-eruption unrest culminated in a strong earthquake on September 29, 1717. Testimonies in the *Autos* unambiguously demonstrate that this was a local, not a regional, earthquake. Moreover, although the earthquake clearly affected parts of the capital city Santiago de Guatemala and was felt to a lesser degree along the Costa de Escuintla (over 70 km to the south), the earthquake was felt most intensely in Alotenango and Ciudad Vieja (that is between Volcán de Agua and Volcán de Fuego; T5; Fig. 4). In fact, some testimonies state explicitly that the earthquake was hardly experienced outside of those towns (e.g., T10), and that the towns most severely affected were those on the slopes of Volcán de Agua (T12). This pattern of impact strongly suggests that the earthquake was caused by faulting related to magma intrusion along a fissure or dyke system propagating east from Volcán de Fuego toward Volcán de Agua, consistent with evidence for eastward propagating dykes during the month of September.

Further evidence for lateral magma propagation lies in the mudflows, which several witnesses thought were triggered by the seismic activity. Evidence for triggering includes emanation of the mudflows from new *abras* on the SW flanks of the volcano (Fig. 6), and descriptions of steaming *avenidas* of water and yellow mud that smelled of sulphur, both of which suggest involvement of a hydrothermal system within Agua's edifice. The mudflows were also accompanied by *estruendos* (crashing, or exploding

sounds), which suggests that small phreatic explosions may have occurred in conjunction with vent formation. These observations, together with the absence of reports of heavy rain, show that the mudflows were not generated by excessive rainfall, but instead by groundwater emerging from within the volcano. Taken together, we conclude that there is overwhelming evidence that a magmatic intrusion from Fuego (probably in the form of a dyke) triggered both the September 29 earthquake and the mudflows from Agua.

5.2 Other examples of cascading volcano hazards involving hydrothermal systems

Magma-induced changes in subsurface hydrologic systems are not uncommon. Manifestations of such changes include phreatic (steam-driven) explosions, changes in hydrothermal systems, groundwater-triggered mudflows and elevated fluxes in local rivers (e.g., Gadow, 1930; Roobol and Smith, 1975; Witze and Kanipe, 2014) or even large landslides (e.g., Voight *et al.*, 1981, 1983; Siebert, 2002). Less common, although not unheard of, is disturbance of a hydrothermal system in one volcano by magmatic activity at a neighboring volcano. Perhaps the most dramatic example of such triggered activity is provided by the 1792 eruption of Unzen volcano, Japan (e.g., Siebert *et al.*, 1987; Siebert, 2002).

Mount Unzen is a volcanic complex that includes the active peak – Fugen-dake – and an older (dormant) peak, the Mayu-yama dome. Fugen-dake erupted on February 10, 1792, after three months of precursory seismicity and phreatic eruptions. Explosive activity gave way to lava flows on March 1; by late April, seismic activity (both felt and heard) propagated to Mayu-yama, 5 km to the east. An earthquake on April 29 caused the dome to slide 200m, and prompted evacuation of the local population. Three weeks later, on May 21, two strong earthquakes triggered a debris avalanche from Mayu-yama that traveled to the sea; the resulting tsunami killed ~15,000 people, making it the most devastating volcanic disaster in Japanese history (e.g., Siebert *et al.*, 1987). In the weeks following the collapse, hot water continued to flow from the scarp, consistent with release of a pressurized hydrothermal system (Siebert, 2002).

The collapse of Mayu-yama dome was probably caused by saturation of the volcanic edifice as hydrothermal waters migrated in front of advancing magma. We suggest a similar scenario for the 1717 mudflows from Agua volcano. As in Japan, both

seismic activity and fissure formation provide evidence of subterranean magma migration between the late August Fuego eruption and the late September earthquakes and mudflows from Agua. Also similar is the emission of over-pressured water (sufficient to form new outlets on the flanks of Agua) from a hydrothermal system (evidenced by the temperature, color and smell of the mud). Importantly, this event was sufficiently unusual that it must have added to the anxiety of the local communities, who were already stressed by the rather severe eruption and the 33 days of subsequent unrest.

5.3 The long shadow of 1541

The events of August-September 1717, although clearly disruptive, were not catastrophic, or even disastrous. Citizens of the area had been living with frequent volcanic and seismic activity since the time of settlement, and some recognized the links between these geophysical events (T36). Why, then, did these events prompt a call from many of the inhabitants of Santiago de Guatemala to relocate the capital city farther away from Volcán de Agua? We address this question by first reviewing the types of information provided by the eyewitnesses and municipal officials regarding previous destructive events related to both eruptions from Fuego and regional seismic activity. We then focus on the specific nature of threats posed by Agua, particularly when placed in the context of the catastrophic 1541 debris avalanche and mudflow.

Volcán de Fuego is frequently active, and has been since the Spanish conquest; in fact, Fuego may have been erupting when the Spanish first arrived in the region (Restall and Asselbergs, 2007). The *Autos* demonstrate that the residents of the area were very familiar with Fuego's eruptive history. For example, witnesses T7 and T8 explicitly mention eruptions earlier in the century, and municipal officials recognize that much of the land was "made by volcanoes" (T17). More importantly, official reports about the 1717 events also include copies of reports made after the 1705 Fuego eruption, with descriptions of the "exceptional quantity of sand and ash that obscured the sun and the daylight", and the statement that more residents of Guatemala have been killed by "fuegos del volcán" than died from human conflict (T46).

Several of the testimonies in the *Autos* also relate to seismic activity. One witness (T17) states that the city of Santiago de Guatemala had to be rebuilt three times since the

16th century because of numerous eruptions and earthquakes, and another (T30) notes that the terrain is ‘sandy’ (covered with volcanic ash) and therefore unstable. Accounts documenting damage caused by the earthquake of September 29 include descriptions of the unusual places where Mass was being celebrated because of damage to churches (T2, T30), the total destruction of Alotenango (T29), the estimated costs of rebuilding Santiago de Guatemala (T32, T41), the decline in taxes collected (T40, T46) and the prominent families who, in December 1717, were still living on the streets because of earthquake damage and fear of further tremors (T37, T44). These statements provide the sound economic argument for relocating the city farther away from the “pernicious” and “nearby enemy volcanoes”.

It is clear from the *Autos*, however, that the mudflows from Agua were considered not only unusual but terrifying. Moreover, the testimonies show that the fears provoked by the mudflows were inflated relative to the actual hazard, and were deeply rooted in memories of the devastating mudflows that destroyed the original capital city in 1541. The 1541 event is specifically invoked by three accounts in the *Autos* (T6, T36, T44), all of which refer to the >600 casualties from that event. Importantly, it is clear that this information was transmitted in both written and form, the latter of which is documented by T36, which are extracts from a book written in 1714 by Fray Francisco Vasquez, a Franciscan friar and historian. In the book he reviews natural disasters that had affected the city since its founding, beginning with the “fatal flood” of 1541. In his description of the event he emphasized the heavy hurricane-generated rainfall that preceded the 1541 mudflows, as well as the terrible noises and ground shaking that accompanied the collapse. Several other witnesses (T6, T7, T8, T10, T12, T13, T15, T16, T18, T21) do not refer specifically to the events of 1541, but did express fears of inundation during the night of September 29. More specifically, witnesses worried about spontaneous generation of mudflows from the flanks of Agua, and consequent blockage of the only drainage from the city (Rio de Magdalena), which ran between the two volcanoes (Fuego and Agua). These fears prompted many to consider moving farther from the volcanoes (T8, T12, T16, T17) and underpinned the consensus of a public meeting on October 20 to request permission to relocate the capital city (T42).

5.4 *Social memory and hazard perception*

The critical importance of the 1541 events in the community interpretation of, and response to, the cascading hazards of August-September 1717 provides a clear example of ‘social memory’ (McIntosh et al., 2000) and the role of past events in determining what is perceived to be a disaster (Slovic, 2000; Bankoff, 2004; Perez, 2001). The time frame of community memory and vulnerability has been recognized (e.g., Oliver-Smith 1986; 2002; Bankoff, 2004) but commonly does not find a place within theoretical frameworks of disaster and change (e.g., Birkmann et al., 2010). This omission reflects (1) recent theoretical advances in disaster studies, which focus on either modern disasters or catastrophic collapse of ancient empires, neither of which provide the time resolution required for studies of the impacts of social memories (e.g., Diamond and Robinson 2010; Cooper et al., 2012); (2) the limited number of historical studies of regions prone to repeated events (e.g., Chester et al., 2012); and (3) neglect, until recently, of social memories preserved within oral traditions (e.g., Masse et al., 2007; Cronin and Cashman 2008; Cashman and Cronin, 2008; Cashman and Giordano, 2008 and references therein).

The 1717 example also shows the power of social memory to drive hazard mitigation. Population displacement (migration) has been a common response to recent disastrous events (Witham, 2005); it also represents an effective long-term strategy for coping with hazards (Riede, 2014). From this perspective, we can view the inhabitants of Santiago de Guatemala as engaging in a response driven not by irrational fears or misperceptions of the actual hazards, but by attempts to employ a rational strategy to reduce their vulnerability to future events. That they are attempting to do this within the restrictions imposed by a colonial structure – restrictions that required extensive evidence-based documentation of the natural events and their impacts – provides a unique window into the workings of social memory in a pre-industrial and semi-autonomous community.

The *Autos* also provide an example of an early systematic survey of both a cascade of hazardous events and their impact. The *Autos* are systematic in the formulaic structure of each testimony, which imposes uniformity on eyewitness data collection that presages the format of social science surveys developed more than three centuries later. Of critical importance to our study are data related to the position of each witness, and

the extent to which the accounts are based on first hand observations or second hand consultation of eyewitnesses. Also interesting is the application of scientific methods to establish, for example, the local origin of the September 29 earthquake, which they did by soliciting accounts from both local and distant (El Salvador) observers. The *Autos* thus provide systematic documentation of hazardous events and their impacts for the purpose of improving both scientific understanding and resilience in the face of future events.

6. Summary and Conclusions

Here we have demonstrated ways in which Spanish archival sources provide key information about both the physical nature of a cascading sequence of natural hazards and a long-term cascade of responses triggered by memories of an early catastrophic event. We have also shown that documentation of the 1717 activity in the form of the *Autos* is unusual from the perspective of natural hazard studies, in that it provides an early example of both a systematic survey of the physical nature and impact of a complex sequence of natural events, as well as a social science survey of human responses to this activity.

The scientific importance of the events of 1717 lies in the clear evidence that magmatic (and associated seismic) activity at Fuego triggered a disturbance of the hydrothermal system at neighbouring Agua. Although not unprecedented (e.g., Siebert et al., 1987), remote triggering of hydrothermal activity is unusual, and raises important questions about hazard assessment of apparently dormant volcanoes such as Agua (e.g., Schilling et al., 2001). Our interpretation of a cascading sequence of hazards transferred from Fuego to Agua also provides a new and integrated perspective of these events. This integrated view contrasts with previous geologic and historic interpretations of the 1717 activity, which consider, separately, the volcanic (e.g., Vallance et al., 2001; Martin and Rose, 1981), seismic (e.g., Feldman, 1993) and hydrologic (e.g., Schilling et al., 2001) events. More broadly, our analysis places the August-September, 1717, activity at Fuego and Agua within a larger framework of volcano-triggered hydrologic hazards that include the under-appreciated hazard posed by interactions between volcanic systems.

The historical importance of this work, from a scientific perspective, lies in the systematic eyewitness accounts assembled in the *Autos*. Organized scientific responses to

volcanic eruptions can be dated to the 1883 eruption of Krakatau, which was followed by detailed studies of both regional and global impacts of the event (e.g., Simkin and Fiske, 1983). Modern social science studies of natural hazards, in contrast, start with seminal work in the 1960s that was summarized by Burton et al. (1978). From this perspective, the *Autos* represent a surprisingly detailed response to a series of cascading natural hazards, particularly given the low physical impact of the events (they did not create a natural disaster). From the ‘long shadow’ perspective, the key observation is that this response – systematic collection of witness accounts from a broad geographic region – can be linked directly to the still-vivid memories of a catastrophic mudflow 176 years earlier. The strength of these memories, as demonstrated by the extremity of the response (a plea by many citizens to relocate the capital city), not only supports Slovic’s (2000) emphasis on memorability as a key element of risk perception, but also shows the potential complexity of responses of past societies to hazardous events. This view supports the idea that natural disasters may be viewed as both historical processes and sequential events (Bankoff, 2004).

Finally, this research also illustrates the limitations of working with archival data. Although the witness accounts provide valuable (and often thoughtful) geologic observations, the descriptions are qualitative and of varying detail. In part this derives from their historical context, and the lack of formal scientific nomenclature for the events described. The language is descriptive and often metaphorical, and thus requires (necessarily subjective) translation into modern scientific language. Additionally, information gleaned from historical sources requires detailed contextual knowledge of the source. In the case of the *Autos*, the critical context is that these witness accounts were collected for the express intent of providing documentation for the Spanish government to support the municipal government’s request to relocate the capital city, which raises the concern that the accounts may be exaggerated. Surprisingly, however, this does not seem to have compromised the veracity of the observations of the events themselves. Moreover, this context likely encouraged the witnesses to include key historical details (about past eruptions, earthquakes and mudflows) that help to explain what appears, initially, to be an extreme over-reaction to a moderate eruption and strong, but not unprecedented, earthquakes and mudflows.

In summary, recent studies have shown the importance of employing the “usable past” (Stump, 2013) to provide immediacy to both hazard forecast scenarios and evidence-based policy recommendations (Reide, 2014). The mudflows from Agua that were triggered by magmatic activity at Fuego provide such an example, and suggest the importance of assessing volcanic hazard from regional, as well as the more typical single-volcano, perspectives. At the same time, this work illustrates the role of memory in risk perception. Understanding communal memories is crucial not only for effective risk communication and improved resilience, but also for inferring causal relationships between hazardous events and apparent responses in historical and archaeological records.

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Figure Captions

Figure 1 Location map showing the three capital cities of Guatemala and the nearby volcanoes. The cities are currently known as Ciudad Vieja (formerly Santiago de los Caballeros, founded in 1527), Antigua (formerly Santiago de Guatemala, relocated in 1542), and Guatemala City (relocated in 1773 following a large regional earthquake). The volcanoes Atitlan, Fuego, Agua and Pacaya lie along the Central America volcanic arc. All have been active during historical times except Agua.

Figure 2 Eruptive history of Fuego volcano since 1524, when the Spanish first arrived in the area. Data are from the Smithsonian Global Volcanism Program database [<http://www.volcano.si.edu/>] and provide a measure of the eruption size using the Volcano Explosivity Index [<http://volcanoes.usgs.gov/images/pglossary/vei.php>]. VEI 4 eruptions of 1717 and 1974 are highlighted, as is the only other VEI 4 eruption between 1524 and 1717, in 1581.

Figure 3 Map showing the approximate location of witness testimonies. Where the witnesses traveled to survey the effects of the different events, they are placed in all relevant locations. See Table S1 (Supplementary Material) for details.

Figure 4 Map showing the witness locations and inferred intensity (yellow, low intensity to orange, high intensity) of the September 29, 1717 earthquake. Key is the evidence from witnesses in El Salvador that they did not feel this event, which means that it was local. Also important is the evidence that the damage was most severe in Alotenango, which lies between the two volcanoes.

Figure 5 Map showing the witness locations and inferred intensity (pale green, low intensity to blue, high intensity) of the September 29 mudflows from Agua. Importantly these flows emanated from the southwest slopes of Agua and traveled south, and thus did not affect the capital city.

Figure 6 Sketch map from the Autos showing the new boccas formed on the flanks of Agua that fed the September 29 mudflows (from witness T23). The witness shows the flows merging upslope of him, splitting around high ground and converging down slope; the flow eventually fed into the Rio Guacalate near Escuintla.

Figure

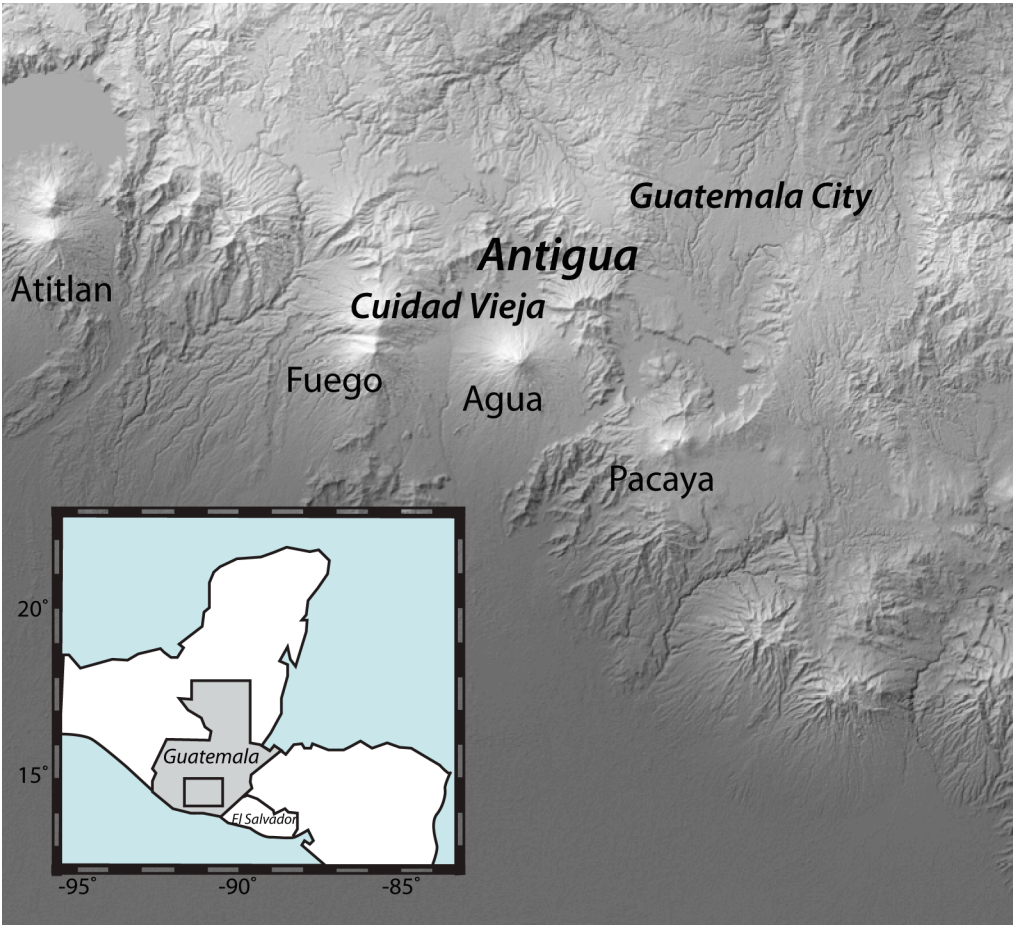


Figure 2

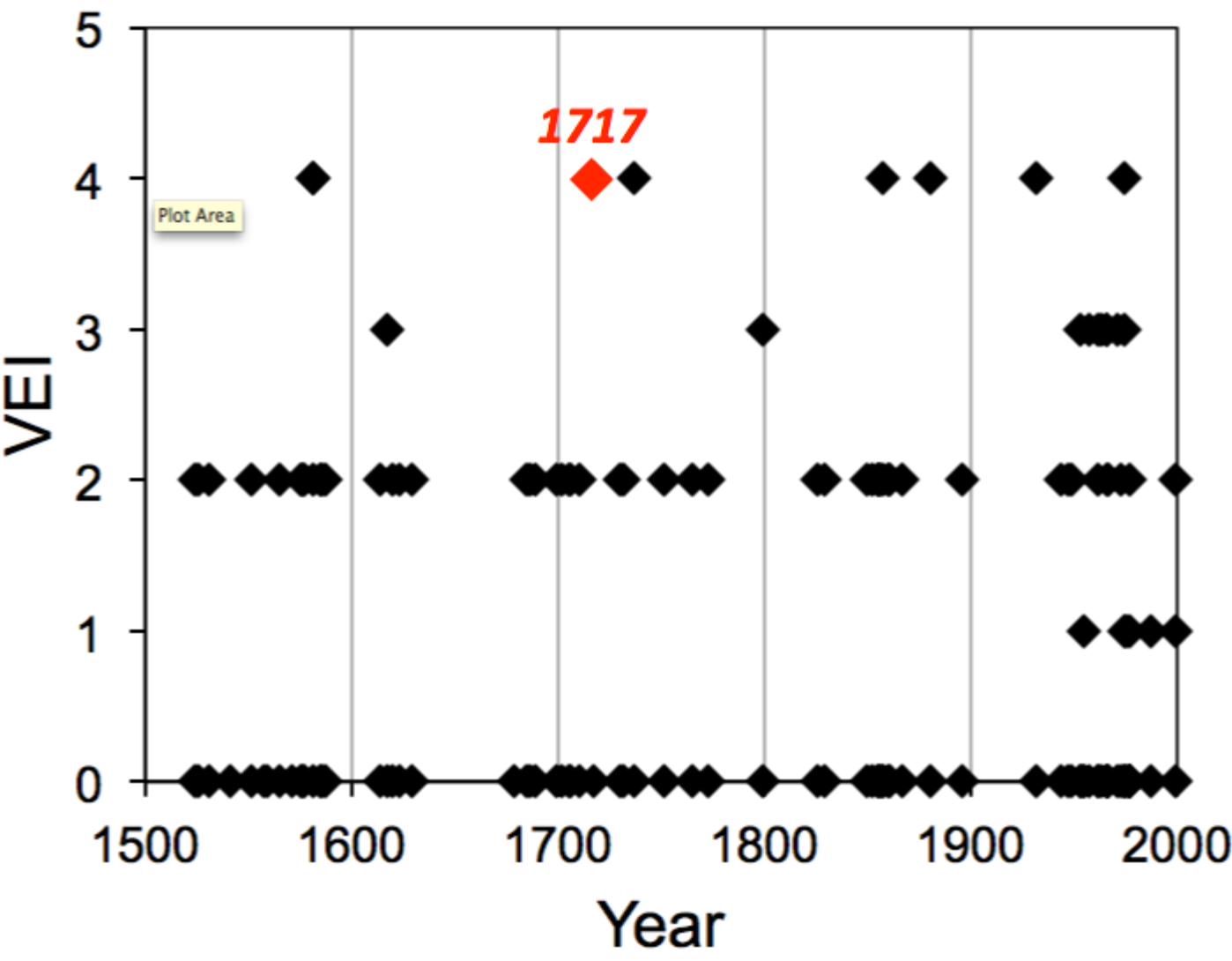


Figure 3

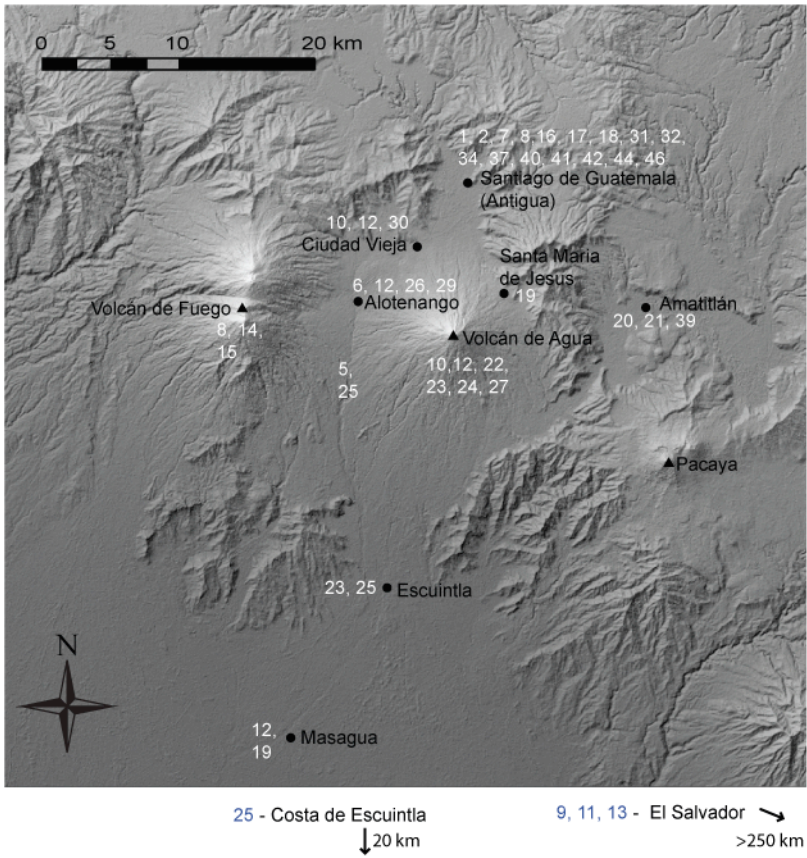


Figure 4

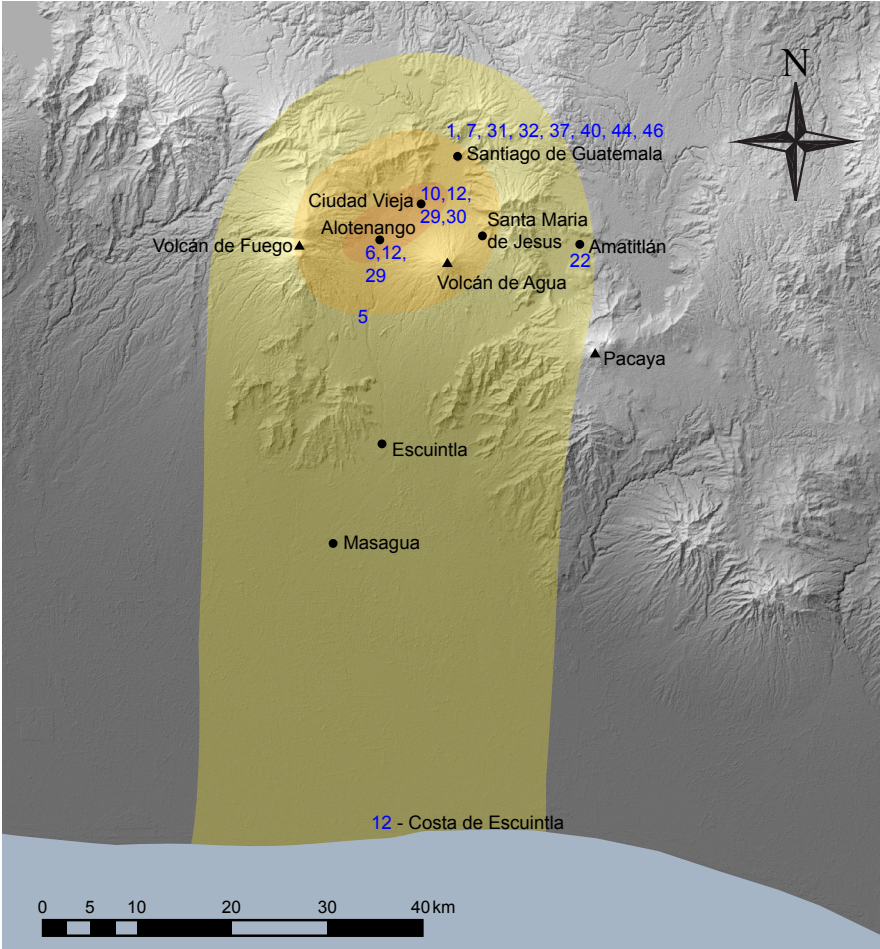


Figure 5

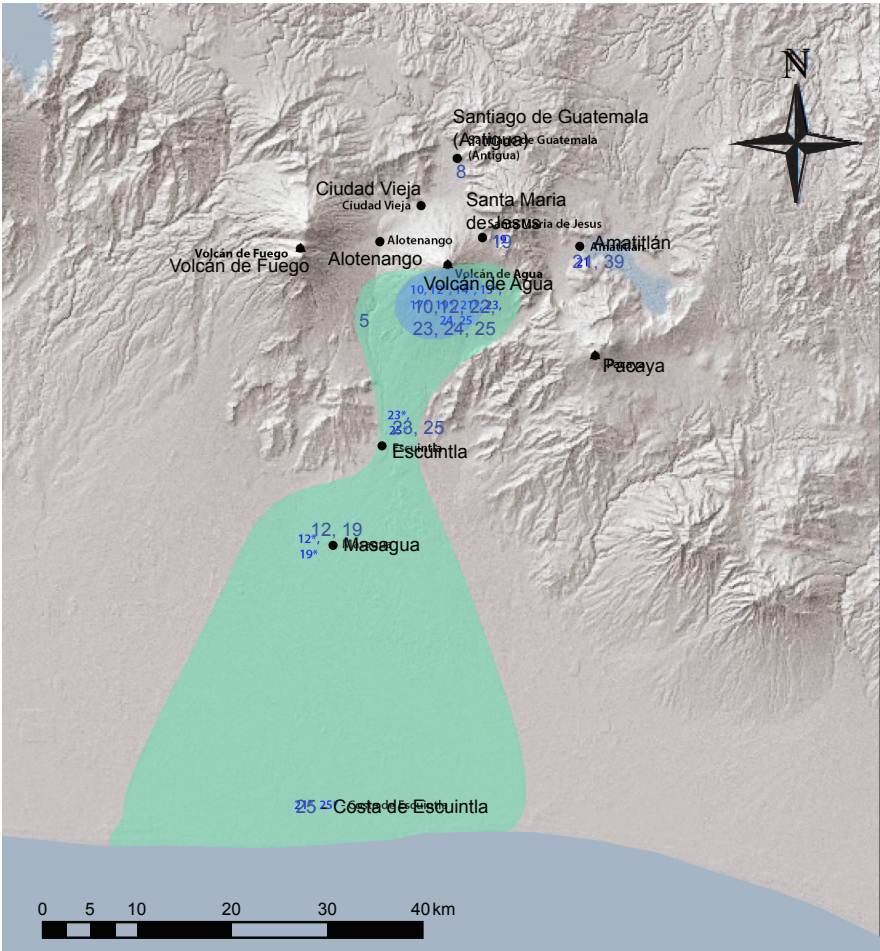


Figure 6



Figure

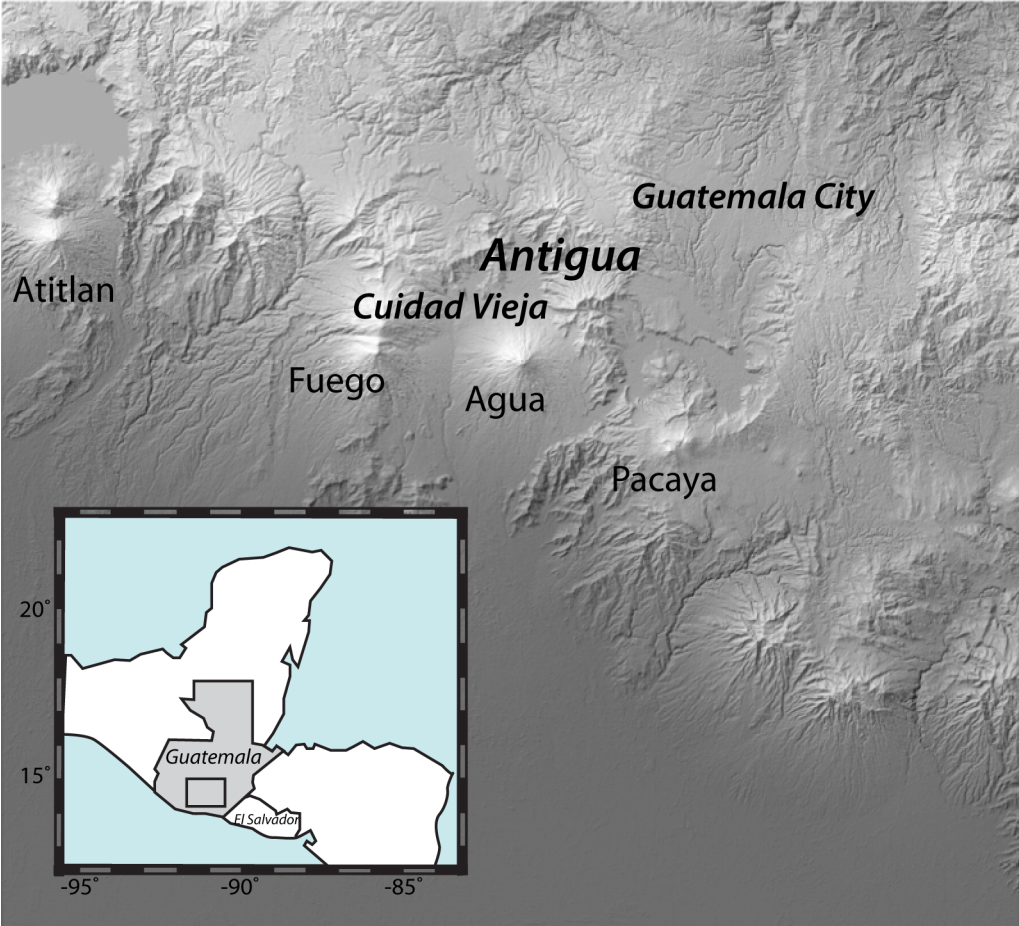


Figure 1

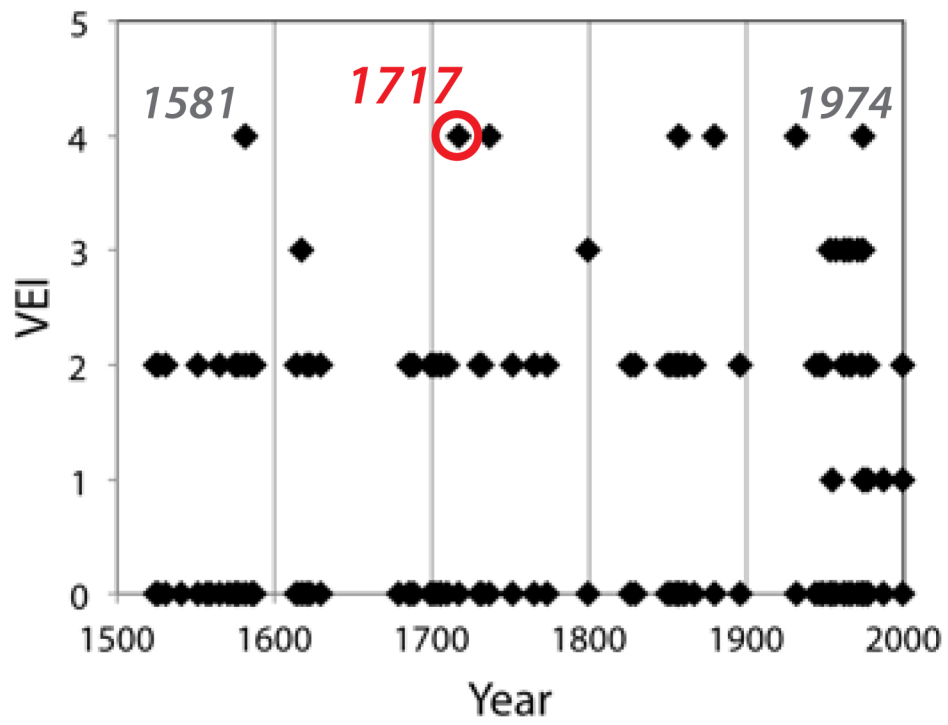


Figure 2

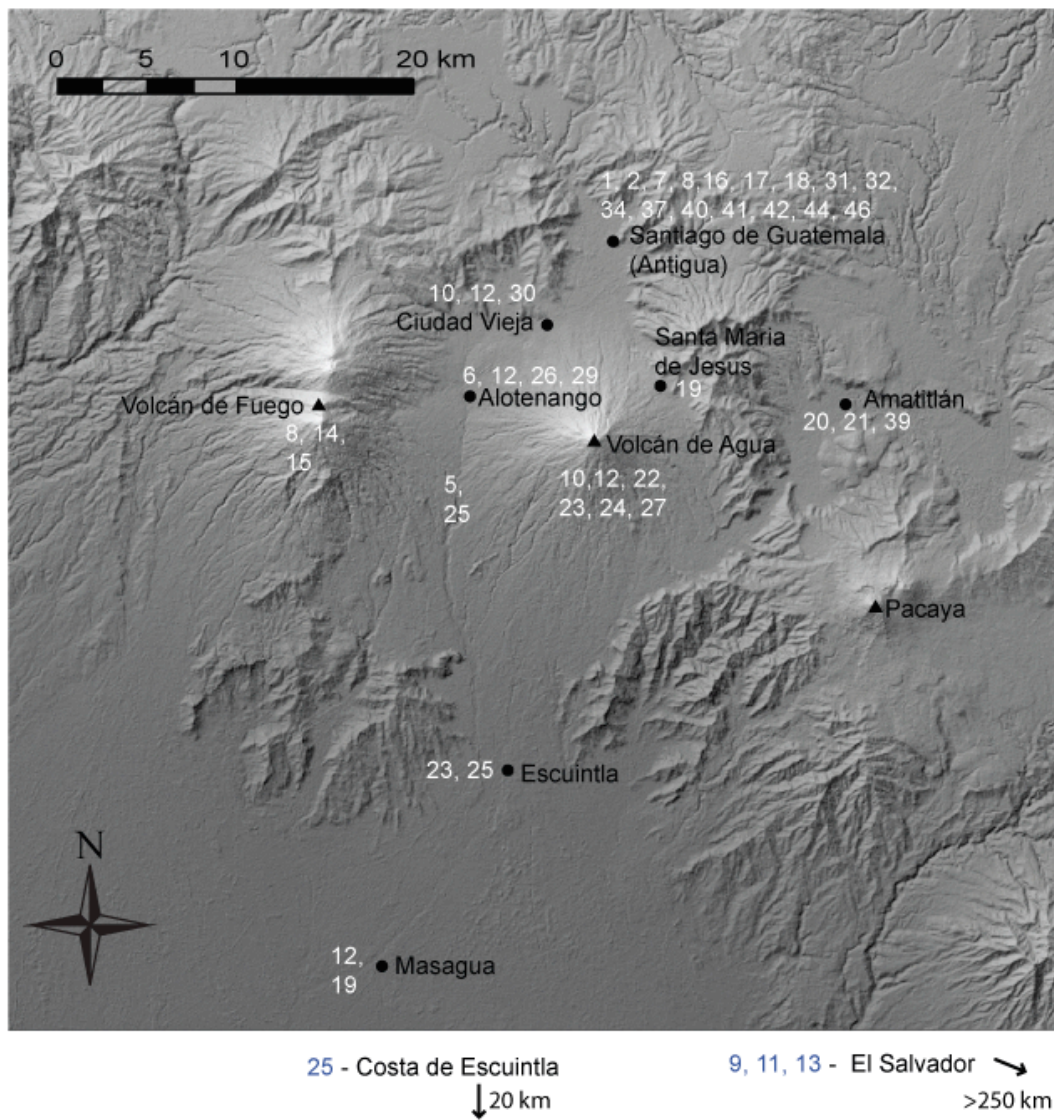


Figure 3

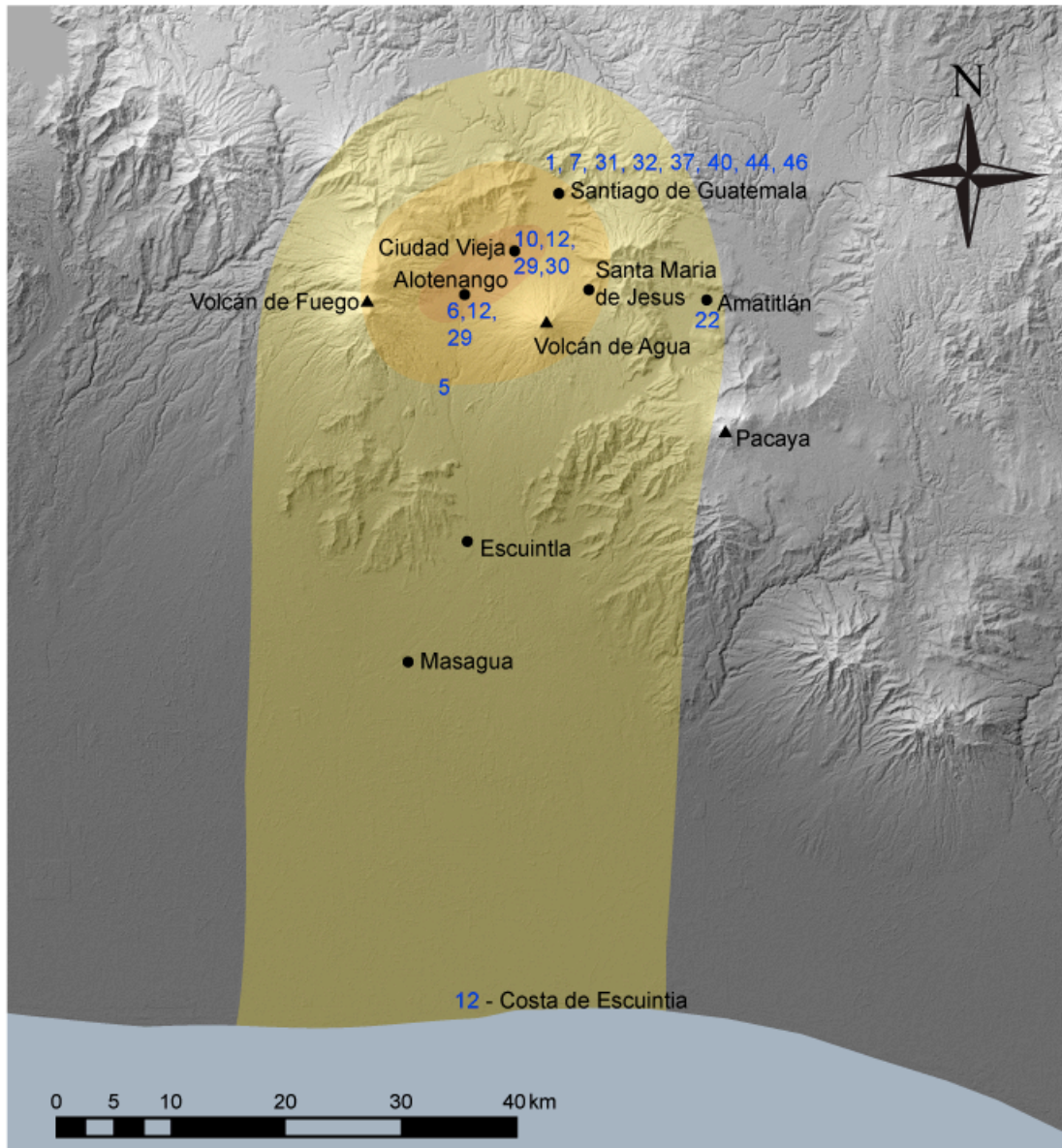


Figure 4

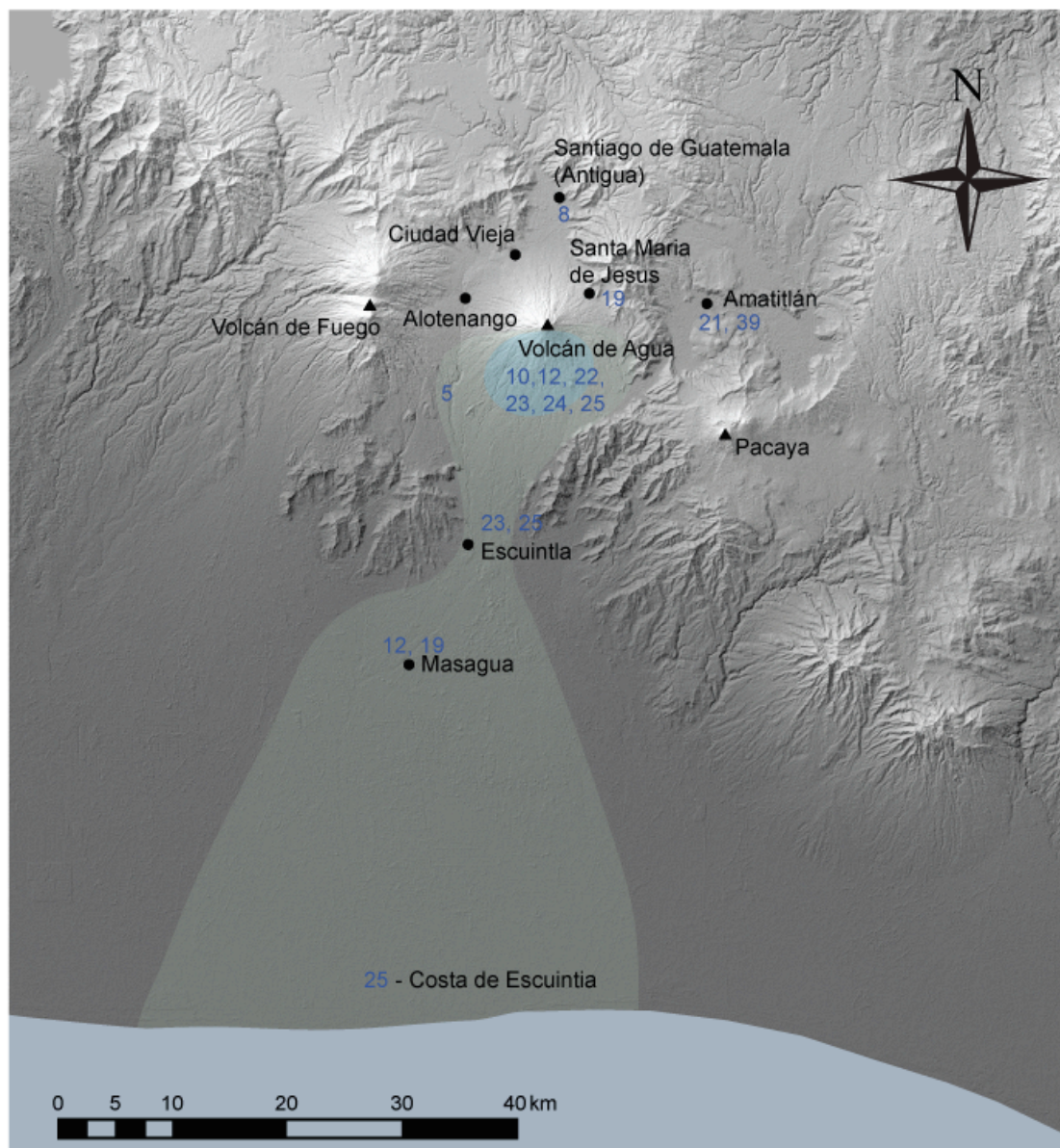


Figure 5



Figure 6

Table - Supplementary

Testimony No.	Folios	Witness	Date (1717)	Occupation; age (if known)	Location at time of events described (where specified)	Location from where reporting on impacts (where specified)	Key points made in evidence
T1	1r-2v	Don Juan Rubayo Morante	25-Oct	Alcalde ordinario, corregidor (municipal official)			Tasked with conducting the investigation into the events of 1717, and collecting evidence in support of the case for relocation
T2	3r-5v	Don Juan Rubayo Morante	25-Oct			Santiago de Guatemala	Reported actions taken in relation to measuring the distance from the centre of the city to the flanks of Agua; describe some of the unusual locations where Mass was having to be celebrated due to earthquake damage
T3	5v-6v	Don Juan Rubayo Morante	26-Oct			Santiago de Guatemala	Reported on measured distance from the centre of the city to the flanks of Fuego
T4	7r-7v	Petition and Licence	26-Oct			Santiago de Guatemala	Permission granted to clergy to give evidence in case
T5	8r-11r	Don Bernardo Valdés	26-Oct	natural y vecino de esta ciudad (native-born resident), aged 39	On his property - located on the slopes of Volcán de Fuego, close to Volcán de Agua, alongside the 'camino real', the main road connecting the city to the coast		Described how the earthquake felt, and other effects and impacts; inspected Fuego; described water debris flow down Agua and Fuego
T6	11r-15r	Don Pedro de la Barreda y Castillo	27-Oct	native-born; resident in the city; aged 31			Reported repeated eruptions of Fuego culminating in that of 1717; carried out inspections; reported concern regarding the potential for debris from Fuego/Agua to block the River Madalena and to cause it to overflow and inundate the city; reported deep sinkholes formed in Alotenango as a result of the 29 September earthquake (a common occurrence); memory of 1541 event leading to the death of 600 inhabitants of Ciudad Vieja
T7	15r-17v	Don Felipe Ximénez	27-Oct	Spaniard; settled in the city since at least 1702	Santiago de Guatemala		Made reference to the 1702 earthquake; eruptions of Fuego in 1705, 1710, 1717; reported rumours in the aftermath of the 29/9 earthquake that Agua had 'burst' at several points, and the fears of inundation that prompted mass evacuation; reported concerns that the city would 'sink' due to terrain sounding hollow
T8	17v-19r	Don Juan Santos	27-Oct	vecino; resident in city for 14 years; 42	Santiago de Guatemala		Made reference to two 1705 eruptions (8 'fingers' of ash deposited on rooftops), and that of 1710; new 'mouths' opened on Agua in 1717; flows/floods in southerly direction
T9	19r-21v	Don Diego Arias de Miranda	27-Oct	priest of San Pedro Caluco, district of Sonsonate; 41	Yzalco		Testified to having seen flames high in the sky on the night of 27 August; experienced no more than a slight tremor on night of 29/9, but a much stronger and longer one on 3/10, the latter considered to have been general (i.e. not attributed to volcanoes)

Table S1 Supplementary Materia

Testimony No.	Folios	Witness	Date	Occupation; age (if known)	Location *	Key points made in evidence (dates in 1717 unless otherwise stated)
T1	1r-2v	Don Juan Rubayo Morante	25/10/1717	Alcalde ordinario, corregidor (municipal official)		Tasked with conducting the investigation into the events of 1717, and collecting declarations to present as evidence in the case for relocation
T2	3r-5v	Don Juan Rubayo Morante	25/10/1717		Santiago de Guatemala	Reported on procedures followed by officials in measuring the distance from the centre of the city to the flanks of Agua; described some of the unusual (deemed unacceptable) locations where Mass was having to be celebrated as a result of the damage caused to the city's churches by the 29/9 earthquake
T3	5v-6v	Don Juan Rubayo Morante	26/10/1717		Santiago de Guatemala	Reported on procedures followed in measuring the distance from the centre of the city to the flanks of Fuego
T4	7r-7v	Petition and Licence	26/10/1717		Santiago de Guatemala	Recorded permission granted to clergy to give evidence
T5	8r-11r	Don Bernardo Valdés	26/10/1717	natural y vecino de esta ciudad (native-born resident); aged 39	On his property on the slopes of Volcán de Fuego and near Volcán de Agua, alongside the main road connecting the city to the coast	Witness experienced the earthquake and retumbos prior to and after the event; inspected Fuego; described water debris flow down Agua and Fuego volcanoes
T6	11r-15r	Don Pedro de la Barreda y Castillo	27/10/1717	native-born; resident in the city; aged 31	Alotenango	Witness reported repeated eruptions of Fuego culminating in that of 1717; carried out inspections; reported concerns regarding the potential for debris from Fuego/Agua to block the River Madalena and cause it to overflow and inundate the city; noted that deep sinkholes had formed in Alotenango as a result of the 29/9 earthquake (a common occurrence); mentioned the 1541 event, and that it had led to the deaths of 600 inhabitants of Ciudad Vieja
T7	15r-17v	Don Felipe Ximénez	27/10/1717	Spaniard; settled in the city since at least 1702	Santiago de Guatemala	Witness made reference to the earthquake of 1702, and to eruptions of Fuego in 1705, 1710, 1717; reported rumours in the aftermath of the 29/9 earthquake that Agua had 'burst' at several points, as well as widespread fear of inundation which prompted a mass evacuation; noted that the primary concern related to the possibility that the city could 'sink' due to the terrain sounding hollow
T8	17v-19r	Don Juan Santos	27/10/1717	vecino; resident in city for 14 years; aged 42	Santiago de Guatemala	Witness made reference to two 1705 eruptions (noting that 8 'fingers' of ash had been deposited on rooftops), and to a further eruption in 1710; noted that in 1717 new 'mouths' had opened on Agua, the flows/floods from which travelled in a southerly direction
T9	19r-21v	Don Diego Arias de Miranda	27/10/1717	priest of San Pedro Caluco, district of Sonsonate; aged 41	Yzalco	Witness reported seeing high flames in the sky on the night of 27/8, and experiencing no more than a slight tremor on the night of 29/9, but a much stronger and longer one on 3/10; noted that this latter one was considered to have been general (rather than being attributed to the volcanoes)
T10	21v-23v	Don Joseph de Sierra y Rebolorio	27/10/1717	vecino; aged 45	Ciudad Vieja on night of 29/9 earthquake; Agua	Witness testified to hearing a loud noise from Agua Volcano on 29/9, such that he believed it to have 'burst'; inspected Agua on 27/10, and reported that an old 'abra' or 'barranca' looking towards Valdes' property [T5] had become significantly wider and deeper, and carried a current of water and debris

Response to reviewers:

Reviewer #1:

This paper represents an ambitious cross-disciplinary effort to understand human and community decision making in the context of natural disasters, or, in this case, a near natural disaster perceived as an actionable portent of future disaster. The method outlined for the research is compelling in that it attempts to interweave multiple timelines--geological, human (decadal), human (centenary)--within a discussion of community risk perception grounded in a specific historical case study. To tease out the relationship between an environmental event such as the 1717 volcanic episode, the "long" historical sequence to which it belongs, and community perception of the relationship between event and sequence, is no small task, and the authors do a commendably lucid and detailed job of explaining why an apparent "over-reaction" to an environmental hazard in fact represented rational risk assessment and logical, adaptive decision-making. The combination of volcanological literature, a social-science framework, and historical data works well, and it is to be hoped will be replicated broadly in disaster studies, and related environmental fields. What is missing from the paper is the next chapter of the story, i.e. the response of the Spanish authorities to the application for the city's relocation. Did the authorities perceive the request as an over-reaction, or as rational and compelling? With this added dimension to the socio-historical narrative, the authors might speculate upon differences, if such exist, between local decision-making processes and the conclusions reached by remote governing bodies based on the "same" evidence. Can risk--particularly the complex, calculated assessment of risk in the 1717 Autos, arriving at a non-intuitive decision--be communicated across distances? In short, what was the fate of the report, and what were the filters through which it was read at imperial headquarters?

While we agree with Reviewer 1 that the next part of the story represents a fascinating question, we specifically do not take the question any further because we know that there are ~~literally at~~ 5 boxes of documents related to the events of 1717 in the archives of Seville alone; these documents are certainly a target for future research (in fact, we hope to find funds to do this) but are also a reason that we are uncomfortable about going beyond our analysis of the *Autos*, which we see as a nicely contained story in itself. For this reason, we merely state at the end of the Background section that “the 1717 evidence-gathering exercise failed to gain the Crown’s support for relocation; it was the major earthquake of 1773 that forced the move of the capital to its current location (Guatemala City; Lutz, 1994)”.

Reviewer #2:

The ms by Hutchinson et al. relates a sequence of volcanological and seismological events that impacted the region of Guatemala City in 1717. The authors base their reconstruction on Spanish chronicles describing the succession of events that occurred from August to September 1717, with a VEI 4 eruption at Fuego volcano, a significant earthquake, and a damaging lahar that descended the flank of Agua volcano. Examination of written archives leads the authors to propose a geological interpretation of the sequence of events, and to elaborate on social memorization processes after the 1524 mudflow at Agua volcano. The manuscript provides a rare and nice exercise in which historical narratives are used to infer a scenario for an unusual sequence of events. On the other hand, I have to confess that I'm not fully convinced by the

resulting geological interpretations, and I suggest considering other options. I list below some points that the authors might want to consider before resubmitting their ms.

1. First of all, the lack of page and line numbers on the PDF file renders reviewing uncomfortable. My comments below come with the PDF page number (P. xx) and paragraph (§. xx) number in the page.

2. A major issue of this work is based on the quality of the translation from old Spanish to current English. The narratives are written in Spanish of early 18th century, with a formulation and a style typically used in administrative colonial documents. As admitted by the authors (P. 21 second §), obtaining a clear view of the 1717 events requires good linguistic skills of colonial Spanish, as well as a robust geological-volcanological background. I think this § should have come much earlier, e.g. in the methodology section, in order to prepare the reader with uncertainties when translating this type of documents. The authors should clarify how the translation was made (who did it?) in light of the above comment.

For example, the term "estruendos" is translated as "crashing, or exploding sounds", but for me "estruendos" would be better translated as "rumbling noises", which makes a significant difference when attempting to interpret the description in terms of source phenomenon. I list other key examples below.

We have adopted this suggestion, and now include an extensive paragraph on language in the Methods section. We pay particular attention to the word “*estruendos*” throughout the manuscript, not only because this word was highlighted by Reviewer 2 but also because the word is sufficiently vague that it requires context for interpretive translation. In fact, we thank this reviewer for prodding us to focus more on the language, which we find more fascinating as we dig into it more deeply. Not only are there issues of popular vs. scientific language, but also there are instances where words had different connotations in the 18th century than in the 21st century. We discuss some (although not all) of these words, and use them to underline our point that historical research in volcanology requires an interdisciplinary effort between scientists and historians.

3. A second point is that the ms provides no evidence that basic field works have been carried out to check/assess some descriptions given in the cited historical narratives. The authors provide no data/constraints/descriptions to show the importance and the dispersal pattern of the 1717 tephra fall from Fuego. Is there any historical record or field evidence that yield information on these points? Was Volcan de Agua also blanketed by the tephra fall? Similarly, it would be important to recognize evidences of surface fracturing and dyke emplacement on the eastern flank of Fuego volcano and on the western flank of Agua volcano, to support the interpretation proposed in the ms. In addition, basic field research focusing on chief volcanological-geological features between Fuego and Agua would bring valuable constraints to help interpreting historical archives. This is lacking in the ms.

We have not done field work. We note, however, that with the frequent activity of Fuego (including 5 VEI 4 events since 1717) and the frequent heavy rainfall in the area, it is unlikely that we would be able to identify and map the specific tephra fall from 1717; it is for this reason that we use the detailed work on the 1974 event, together with the detailed descriptions in the *Autos*, to define the activity. It is possible that field work could be used to identify deposits from the 1717 mudflows, although these may also be overprinted by more recent events, and mudflows are notoriously difficult to date (e.g., Pistolesi et al., 2013).

4. The term "barrancas" is translate as "ravines" in the ms (P. 9), but is essentially interpreted as ground fissures (P. 9). However, in Latin America (and in colonial texts) this term is typically used for "gullies" or "ravines" formed by running waters and torrents, while the term "grietas" is preferred to describe open fractures/fissures. To me, the "barrancas" described in the ms are not the surface expression of a propagating dyke, but typical gullies and ravines that were formed or modified during and after the 1717 eruption of Fuego.

We agree with this interpretation and have modified the text accordingly.

Major morphological changes are extremely common during and after VEI 4 eruptions at tropical steep-sided volcanoes, as ravine (bedrocks and sidewalls) erosion occur during pyroclastic density current (PDC) and later lahar emplacements. This leads to deeper and wider gullies on the edifice's upper slopes. Concomitantly, erosion and sedimentation on the lower slopes translate into valley filling/carving processes, overbanking effects, formation of new ravines, and finally to modification of the local drainage system. The steam reported in the archives could be as well interpreted as water vapor escaping from hot pyroclastic debris that accumulated in the "barrancas". The term "llamas" (flames above Fuego's summit crater as seen from Santiago de Guatemala) is classically used in colonial texts of Latin America to describe tall lava fountains that most likely generated scoria flows and ballistic ejecta on the slopes of the volcano. Steaming of hot pyroclastic deposits in ravines for days to weeks after eruptions of substantial sizes is a common phenomenon, notably at volcanoes in humid countries. The fact that such "barrancas" formed on other sides of the volcano support a similar process, instead of another dyke that could have propagated at right angle to that between Fuego and Agua. The "brecha" (breach) that formed from the summit of the volcano to the east is interpreted as a fracture opened on the eastern side of the edifice. Indeed, the formation of a summit notch, in which the pyroclastic material is channelized during an eruption to flow downslope along a preferential pathway, is a common process at many conical (basaltic/andesitic) volcanoes worldwide, as at Semeru in Indonesia, Mayon in the Philippines etc. Examination of the eastern base of Fuego volcano on Google images reveals the existence of a conspicuous, geologically fresh-looking sedimentary fan just south of Alotenango village. This fan is likely made of PDC deposits and/or debris flow/laharic breccias, and was possibly (partly) formed during the recent 1717 eruption. As written above, a field study should check these features to help interpreting the historical narratives. Similarly, "abras" is translated as "openings" and is interpreted as superficial pits and small collapse structures that formed as a result of dyke propagation. However, the term "abras" may as well describe the source areas of landslides where vegetation has been removed, leaving arcuate-shaped scarps similar to that of open pits. Again, this is common during eruptive periods at this kind of tropical volcanic edifices, when erosion is boosted/enhanced as a result of sedimentary disturbances related to the eruptive process.

We agree with the reviewer that the gully widening and steam reported on Fuego's eastern flanks immediately after the 27-29 Aug eruption are likely the result of pyroclastic flows from the eruption itself (which we state clearly in our interpretation of the accounts). We also note that the widespread description of the sensation of walking on "hollow ground" could be ascribed to the same pyroclastic flows. Our interpretation that subterranean magmatic activity may also have been occurring during this time period derives from the clear evidence for continued seismic activity (both *retumbos* and *temblores*), as well as the subsequent events of September 29-30 (as described in the text). In fact, we have had long discussions about the possible meaning of 'abras', which simply means 'openings'. In the witness statements, however, it is clear that 'abras' is used specifically (and uniquely) to describe the source of the mudflows at Agua associated with the 29/9 earthquake; the word is associated with descriptions of Agua

‘bursting’ (e.g., T7, T10, T18), as well as descriptions of new ‘mouths’ (vents) on Agua (T8) and the instruction to ‘pay particular attention to Agua and the matter expelled therefrom’ (T18). Taken together, we find the language to indicate that the mudflows from Agua were *not* rainfall-triggered mudflows of new ash but instead were internally generated (and therefore more terrifying to the inhabitants). We now support this interpretation more fully, and supply more detailed descriptions in the Table provided as Supplementary Material. We also add the observation that water continued to flow from these new openings for weeks (T22, T23), a feature that is not consistent with rainfall-induced landslides/mudflows.

5. If I understood well, the authors interpret the term "bóveda" mentioned by some people between Fuego and Agua volcanoes as hollows that reflected cavities formed as a result of dyke emplacement between both volcanoes. It is unclear to me how such cavities could have formed there without clear structural surface expressions, as usually happens at the tip of shallowly propagating dykes, and I wonder why this is not preserved in present-day geomorphological features of the area. I suggest another interpretation. Such impression of porous grounds is typically perceived when walking on fresh unconsolidated deposits of small-volume pyroclastic flows, and even more on non-compacted (but dewatered) debris flow and lahar deposits. Recently emplaced loose material can have acoustic properties that give the feeling of some open space below the surface. This is a strange sensation and the description given in the ms recalls several experiences I had on freshly emplaced, unconsolidated deposits at tropical volcanoes. Now, I speculate that such unconsolidated deposits may correspond to (a part of) the sedimentary fan south of Alotenango. I suggest that these deposits could have been the source of the strange sensation that the people perceived while crossing (may be with horses or cattle) the area between Fuego and Agua.

We now include this interpretation in the text.

6. According to the interpretation proposed in the ms the "estruendos" are produced by small phreatic explosions and opening of small vents along the path of the propagating dyke from Volcan de Fuego to Volcan de Agua. As indicated in my first comment above, I would translate "estruendos" as "rumbling noises" that are expected to occur when a large debris flow is in motion. Collisions/frictions of blocks and boulders in lahars and debris flows always produce an impressive acoustic signal (that can be heard kms away from the source) and ground shaking is commonly perceived by witnesses in the vicinity of the lahar/debris flow channel.

We now discuss our interpretation of the word “*estruendos*” in much more detail in Sec. 5.1. Importantly, we provide contextual information to suggest that the *estruendos* may refer to more than simply the noise of debris flows. We also note that the sketch provided in Figure 6 clearly demonstrates that the mudflows emerged from new vents on the SW side of Agua; whether or not those openings were accompanied by the noise of explosions is thus a detail (and not critical to our argument that opening new mudflow vents requires a disturbance to the hydrothermal system within Agua). For this reason we have omitted mention of phreatic explosions.

7. The authors claim that the mudflows from Agua "were hot enough to kill all of the fish in the river". To me this sounds like an over-interpretation because it not know if other fishes were still alive, and actually the cause of death is not made clear: it could be the heat, but could be as well an excess of clay accumulation in the water, or a lethal concentration of poisonous elements that

commonly accumulate in hydrothermal systems (notably halogens and heavy metals), or a combination of these different factors.

We have removed this statement.

8. The authors try to convince that the September 29 earthquake was local. However, from the material provided in the ms I'm not persuaded that the "Autos unambiguously demonstrate" that the event was local, instead of regional. An earthquake felt 70 km away on the Guatemalan coast with strong damages in Guatemala City is best explained by a tectonic event. The bias in the impression that the effects were stronger between Fuego and Agua may be due to the strongly non-homogenous distribution of the population at that time, giving rise to more detailed accounts in the region of Fuego and Agua volcanoes. I largely agree, on the other hand, that the earthquake might have played a major role in triggering the landslides and subsequent mudflows at Agua.

First, there is explicit discussion in the *Autos* about the regional vs. local nature of the earthquake. The *cabildos* were clearly well acquainted with regional earthquakes – in fact it was the regional earthquake of 1773 that finally prompted relocation of the capital city of Guatemala to its current location – and therefore they explicitly set out to determine the earthquake origin. They conclude that the earthquake was local and not regional. Second, we report only mudflows from Agua, not landslides. Additionally, Figure 6 makes it very clear that the source of the mudflows was not a landslide(s) caused by the local shaking; instead, the mudflows issued from discrete (and new) openings on the side of the volcano, without evidence for widespread slope destabilization. Moreover, seismically triggered landslides would not be expected to form mudflows until they reached (and mixed with) water in river valleys. The description of witness T23 are clearly of mudflows, and mudflows where he did not expect them.

9. To me the hypothesis of a propagating dyke needs a much stronger substantiation, i.e. would require arguments that go beyond the (disputable) translation of colonial archives. Examination of Google Earth images suggest that there are no flank vents at Fuego and Agua volcanoes. Breaching Fuego's eastern flank without formation of a lateral vent on the slope of that volcano sounds like an uncommon volcanological situation. Extending a dyke more than 12-13 km to the east toward the top of Agua's edifice without meeting the topographic surface between both volcanoes is difficult to imagine. In addition, the authors provide no geophysical evidence/reference to check if the propagation of a dyke is consistent with the tectonic stress regime in the region. In fact the supposed dyke would be perpendicular to sigma 1 produced by the subduction stress field. Dyke formation along a North-South-trending fissure, sub-parallel the subduction velocity vector, looks more likely, as is corroborated by alignments of Fuego and Acatenango crater systems.

We have softened the tone of our writing to present our hypothesis as just that – an hypothesis – that appears to fit the data provided by the witnesses. In particular, we emphasize (1) the period of unrest between the eruption of Fuego and the Sept 29-30 earthquake and mudflow, (2) the coincidence of the earthquake and mudflow, (3) the severity of the damage in the region between the two volcanoes, (4) the unusual location of the (new) mudflow vents, and (5) descriptions of the mudflows (the ‘bursting’ of Agua, the new ‘openings’ and the continued flow of water from those openings [‘the matter expelled from within’]) that suggest that they involved Agua’s hydrothermal

system. This interpretation relies on ~~but does not affect~~ the eyewitness accounts, which form the basis of our paper. Clearly they are open to other interpretations – it is for this reason that we provide Table S1 as a guide to anyone interested in doing more work on these documents.

10. I found the section on social memorization of interest, and I concur with the authors that some historical descriptions might be exaggerated for the purpose of influencing the decision regarding the relocation of the second capital city. On the other hand, I was expecting a more general discussion in which other volcanic disasters could have been considered for comparison (e.g. Vesuvius 79, 1631 etc.) notably in Latin America (e.g. Mexico, Ecuador, Peru), where similar studies combining history/volcanology/natural disasters have been previously conducted.

Although the use of historical documents elsewhere is interesting, we felt that a discussion of this would be a bit off topic. In most volcanological studies, historical documents have been employed only to determine the timing, and sometimes the nature, of eruptive activity (e.g., Siebert et al., 1987; Thouret et al., 2002; LePennec et al., 2008; Pistolesi et al., 2011). Alternatively, anthropological use of oral and written records has focused on the impact of and response to hazardous events, but without detailed assessment of the events themselves (e.g., Cashman and Giordano, 2008; Chester, 2012). Our study is unusual (1) in the nature of the documents, ~~which are ain that, to our knowledge, they represent a unique (?)~~ compilation of 18th century documents that combine multiple observations of both natural events and their impacts, and (2) the insight they provide into the long-term impact of a catastrophic event (here the 1541 landslide) on a community. We have tried to make this point.

In summary, while I really found the ms of interest, I have to say that I was not convinced by the geological interpretation proposed by the authors. I think the authors should reconsider the translation of key terms used in historical archives, check some speculative issues discussed in the text, and combine with additional volcanological and geophysical constraints to offer a stronger interpretation of this otherwise nice compilation of historical data.

Below I list some other minor points.

P. 3. Reference to Sheets and Grayson (1979) seems a bit outdated, more recent references on archeology and volcanology could be added here.

We ignored, as instructed.

P. 4. Background. End of §; well, here the considerations regarding "community planning and perception" do not consider (potentially animistic) beliefs and religious aspects of community cultures, which may largely contribute to explain how communities cope with volcanic disasters (e.g. acceptance of "fatality").

We agree (and have considered this elsewhere) but it does not seem to be particularly relevant to this paper (the *Autos*, in fact, counter the concept of fatality in that members of the community are actively promoting relocation).

P. 5. Background. End of 2d §. "The mudflows have affected the area to the north of the

volcano", does it mean that only the north has been affected? Or is it a biased impression owed to the fact that the witness was in Ciudad Vieja located north of the volcano?

Although we have not done an exhaustive search of the documentary evidence, all recorded (including recent) rainfall-triggered mudflows do appear to derive from the north flank, exclusively.

P. 5. Background. End of 3rd §. The authors write that inhabitants were very familiar with Fuego's activity. What does this mean precisely and how should this be interpreted in terms of community reaction when facing nuisance/danger from the volcanic activity?

The inhabitants' familiarity comes out in the descriptions of the *Autos*; for this reason we prefer, in the Background, to simply point out the frequency of historic activity (that is, to provide direct documentary evidence that eruptions of Fuego were part of daily life). The supplementary Table also provides some explicit mentions of eruptions from Fuego in 1705 and 1710 (T7, T8).

P. 5. What is the argument to write that the debris flow evolved downward to a mudflow? Any constraint on how much "unusual" the "heavy rain fall" was? Any quotation to support this assertion?

We provide the reference of Schilling et al. (2001) for this interpretation.

P. 5. end of 3th paragraph. Last sentence "it is this event ... that is the subject of this paper".

We are not sure what this comment means?

P. 6. 2d §. Well, the study does not show that eruption at one volcano triggers activity at another volcano.

As noted above, this is our interpretation (and we are clear that this is an interpretation).

P. 8. The authors should say somewhere that Fuego's and Agua's summits are frequently obscured by meteorological clouds, and it is likely that the acoustic activity was described in more details when the volcanoes were cloudy.

This is an interesting point but is also speculation. Instead of making this point we have expanded our explanation of all of the words used to describe sounds.

P. 8. End of first §. Why collapse of the front of an "advancing lava flows"? Any evidence of these 1717 lavas preserved in the geological record of the volcano? Why not typical "scoria flows" that are expected to occur during a strong VEI 4 lava fountaining event on a steep-sided volcano?

We have modified this statement.

P. 8. En of first §. "Relatively close", please provide approx. distances to help the reader interpret what "relatively close" means.

We have modified.

P. 8. Vecinos is usually used in Spanish for "neighbors".

We now explain the colonial Spanish use of this term in the Methods.

P 8 last line: veinte (instead of "viente")

Now corrected.

P. 9. Section 4.2. Apart from barrancas what are the original Spanish terms used in the archives to describe "ground fissures"?

Again, we have explained the terminology more thoroughly.

P 9. To me this section describes the enlargement of a ravine, not the emplacement of a dyke. The ravine was formed previously and the eruption gave the conditions for morphological changes (erosion, deepening and widening during PDC emplacement and lahar activity). The witness noted that the barranca was clearly the passage of lahars that transported tree logs and branches, as is common at tropical volcanoes.

We agree and now say explicitly that the ground cracks may have had multiple origins.

P. 10, last two paragraphs. The barranca to the south might well be a similar enlarged-deepened gully that contained still hot pyroclastic material to produce steam in the wet Guatemalan environment. To me this describes a typical PDC deposit in a ravine that cools and emits steam. That is fine – we now say this.

P 12. Last § in section 4.3. What is the argument to infer that the witnesses in Santiago de Guatemala are exaggerating the intensity-destruction of the earthquake in the city (T32 gives detailed descriptions)?

We only note that there could be bias, not necessarily that there was.

Fig. 6 shows a series of 3 distinct "abras" from the summit area, as is expected to occur after local (potentially seismically-triggered) landslides, not really after emplacement of a dyke.

Our interpretation is based on the clear description of these features as mudflows rather than earthquake-triggered landslides. We agree that this is an interpretation, and have provided data that we believe supports this interpretation.

p. 13. What "typical rainfall-triggered" mud flows at Agua look like? Might be important to provide some original sources in Spanish here.

We have not had the opportunity to go through the entire archives to look for this. We do have sources that describe rainfall-triggered mudflows in the late 17th and early 18th centuries, but feel that introducing these would stray from the focus on the *Autos*. Instead, we include a reference to the most recent rainfall-triggered mudflows from Agua, which occurred in response to intense rainfall produced by Hurricane Agatha and which traveled down valleys on the north flank of Agua, and into Ciudad Vieja (the site of the first capital city).

P 14 first line. The term "tremors" has a precise meaning in volcano-seismology and sounds too interpretative here. A more descriptive term as "ground shakes" or "vibrations" sounds more appropriate here.

We disagree that “tremors” has a precise meaning in volcano seismology – it is the singular use of the term (i.e. “tremor”) that is precise, referring to long-duration, low-frequency ground vibrations; this specific term is not pluralized to “tremors”.

P 14. End of first paragraph. "That" is repeated twice.

Corrected.

P 14 section 5.1. It would be useful to provide some elements about the dispersal of the tephra cloud from Fuego. Direction of the main dispersal axis? Lateral distribution? Any historical/field constraints on tephra thickness at some localities? Was Agua volcano blanketed by Fuego's tephra fall deposits? (Could facilitate the onset of mudflows).

We have no data to make such estimates. We note that the tephra blanket from the 1974 eruption was dispersed toward the SW (that is, away from the communities surveyed for the *Autos*). In fact, it is an interesting point that although there is some mention of problems with ash in Santiago during the eruption, there is no other mention of ash problems, which might be expected if quantities of ash equivalent to those produced in 1974 had been deposited to the east.

P 15. End of 3th paragraph. Which towns "on the slopes of Volcan de Agua" exactly? Currently all towns are located at the base of Agua, with a few villages on the lower slopes, and I wonder about the situation in 1717.

We have only the descriptions in the *Autos*; we suspect that most of the villages were located close to the main valley between Fuego and Agua.

P 15. Beginning of 3th paragraph. The new "abras" are not necessarily collapse pits at the tip of a propagating dyke, they may simply describe landslides that scorched the upper part of the volcano, as is common on steep-sided edifices in tropical countries. Steaming avenidas could be enlarged gullies and ravines filled with hot pyroclastic material, and not necessarily - in my reinterpretation of the material provided in the ms - the surface expression of a propagating dyke.
P 15. End of page. I agree that these yellowish products and sulfur smells support involvement of material from a hydrothermal system.

Here we have expanded our descriptions of the witness accounts and reserved our interpretation for the end of the section; we are glad that the reviewer does acknowledge the involvement of the hydrothermal system.

P 16. Is the absence of "heavy rain" reports a good criteria? Could be raining on the top of the volcano, but not near its base.

OK – absence of evidence is not evidence of absence, but other well documented mudflows from Agua have involved intense rainfall, which would have been recorded (particularly because at least some of the witnesses were clearly well aware of the sequence of events in 1541). For example, the torrential rains that preceded the 1541 disaster are well described. Additionally, rain at the mountain's summit would be unlikely to produce descriptions of bursting, new openings, and continued emission of water from these openings for weeks.

P 16. Not clear in the text if the lava at Fugen Dake was a lava flow or a lava dome. No references to Japanese works here?

The Siebert reference includes a summary of the Japanese accounts.

P 17 section 5.3. First sentence. Well, the people who lost their houses and crops at that time may have a different assessment of whether these events were catastrophic or not.

We use “catastrophic” as applied to the community as a whole (the common use of catastrophic).

P 18. 2d paragraph "Written and (oral?) form"

Corrected.

P 19. Some comparisons with well-documented volcanic disasters (e.g. Vesuvius) would be welcome here to discuss the social memorization process.

Discussed above. Actually, Vesuvius is an interesting case because the catastrophe is not well recorded in Roman literature except by Pliny the Younger. In fact, there seems to have been very little memory of that event (as far as we understand... we are not Italian scholars). David Chester has worked extensively at Mt. Etna to examine changing perceptions of volcanic activity there – we do mention his work but not in the Discussion. However, our work does provide a case study that contrasts with his, which is the response of the state (as compared with local community) to an emergency. In fact, we plan to build on his Etna work when we have the opportunity to investigate the entire archive related to the 1717 events.